

The effect of variable stellar magnetic fields on the spin state of T Tauri stars

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ABSTRACT

Understanding the stellar spin evolution of young stars is crucial for understanding the evolution of protoplanetary disks and, consequently, the formation of exoplanets. According to stellar spin models, T Tauri stars should evolve toward a spin equilibrium in which the external spin-down torque balances both the external spin-up (accretion) torque and the spin-up due to stellar contraction. A useful reference point along the way to this equilibrium is the “zero-torque state” (ZTS), at which only the external torques cancel out. Recent observations, however, have shown that the spin state of a considerable number of stars is shifted out of the spin equilibrium and the ZTS. We investigate the effects of variable stellar magnetic fields on the stellar spin state of T Tauri stars. The long-term decrease (0.1–2.0 Myr) in the stellar field strength due to the formation of a radiative core and short-term stellar magnetic cycles (10¹–10⁴ years) are taken into consideration. Both scenarios are studied using an implicit disk evolution code capable of modeling the magnetic star–disk interaction in the innermost disk and the stellar spin evolution self-consistently over long timescales. Temporal variations in the stellar magnetic field can significantly affect the stellar spin state of T Tauri stars. The strength of the effect on the stellar spin state depends on the relation between the timescale of the changing magnetic field, the spin-up timescale, and the viscous timescale of the accretion disk. A developing radiative core on a timescale shorter than the spin-up timescale has a strong effect on the spin state. Stellar magnetic cycles on timescales shorter than the viscous timescale of the inner disk have a weaker effect on the stellar spin state due to a slow back-reaction of the accretion disk. Our results can explain (at least) a part of the stars that are observed out of both states. Further theoretical and observational work is needed to connect accretion, stellar rotation, and magnetic properties in T Tauri stars.

Key words. accretion, accretion disks – stars; protostars – stars; rotation

1. Introduction

To understand the formation and evolution of exoplanets, we require insights into the early processes in classical T Tauri stars (CTTSs; $M_{\star} \lesssim 2 M_{\odot}$) and their surrounding protoplanetary disk (PPD) that shape the cradle of young systems. The stellar spin distribution observed in CTTSs poses an ongoing challenge. Observations show rotation periods ranging between ~ 1 and 10 days (e.g., Rebull et al. 2006; Herbst et al. 2002; Cody & Hillenbrand 2010; Venuti et al. 2017; Rebull et al. 2020; Serna et al. 2021; Smith et al. 2023). During the CTTS phase, young stars actively accrete material from their PPDs, increasing their angular momentum (AM), and the stars contract, which should lead to a spin-up (e.g., Rebull et al. 2002). The rotation distributions of young stars, however, remain relatively constant over the expected PPD lifetime of $\lesssim 10$ Myr (e.g., Smith et al. 2023) and show a spin-up after most PPDs have dissipated (e.g., Gallet & Bouvier 2013).

To prevent the spin-up of CTTSs, the magnetic star–disk interaction presumably removes stellar AM (e.g., Koenigl 1991). In early studies, the disk was assumed to be “locked” to the star, removing stellar AM (e.g., Ghosh & Lamb 1979; Shu et al. 1994). This “disk-locking” mechanism, however, has since been found to be too ineffective to explain the observed spin distributions (e.g., Agapitou & Papaloizou 2000; Rebull 2001; Matt & Pudritz 2005b; Herbst et al. 2007; Zanni & Ferreira 2009). In more recent models (e.g., Romanova et al. 2018;

Gallet et al. 2019; Ireland et al. 2021; Takasao et al. 2022, 2025; Zhu 2025), stellar AM is removed by outflows in the form of magnetospheric ejections (MEs; Zanni & Ferreira 2013), conical disk winds (CDWs; e.g., Romanova et al. 2004b; Lii et al. 2014; Romanova et al. 2018; Takasao et al. 2025), and accretion-powered stellar winds (APSWs; e.g., Matt & Pudritz 2005a; Matt et al. 2012; Finley & Matt 2018). The amount of AM that can be removed from the star depends on the relation between the inner disk (or truncation) radius, r_t , and the corotation radius, $R_{co} = (GM_{\star}P_{\star}^2/4\pi^2)^{1/3}$, where $M_{\star}$ is the stellar mass and $P_{\star}$ is the stellar rotation period (e.g., Romanova et al. 2009; Gallet et al. 2019; Ireland et al. 2022; Takasao et al. 2022, 2025). This relation is often parameterized with the fastness parameter, $\omega_s = (r_t/R_{co})^{3/2}$ (Ghosh 2007). The magnetic field strength of a young star plays a crucial role in its spin evolution, as it controls the net amount of AM that different spin-down mechanisms can carry away (e.g., Zanni & Ferreira 2013; Gallet et al. 2019; Ireland et al. 2022; Takasao et al. 2025) and the location of the truncation radius, r_t (e.g., Hartmann et al. 2016), influencing ω_s .

With an increasing value of ω_s , the spin-down mechanisms can carry away more AM from the star (e.g., Ireland et al. 2022; Takasao et al. 2025), resulting in a stabilizing effect on the stellar spin. For a star with a given inner disk radius, r_t , a fast rotation period leads to a small R_{co} and a large ω_s . Consequently, the spin-down mechanisms are removing stellar AM efficiently, causing the star to spin down and decreasing the ω_s . Similarly, a star that spins slowly, equivalent to a small value of ω_s , spins up.

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A further consequence is that the external torques on the star tend toward a balance, the so-called zero-torque state (ZTS) at which external spin-up (e.g., accretion torques) and external spin-down contributions cancel each other out (e.g., Pantolmos et al. 2020; Ireland et al. 2021, 2022; Takasao et al. 2025; Zhu 2025). A star in a ZTS, however, is still subject to spin-up from contraction. Stars therefore evolve toward a spin-equilibrium state, in which external spin-down balances both the accretion torque and the contraction-driven spin-up. This equilibrium is reached at a fastness parameter larger than that of the ZTS, with the exact value depending on the stellar torque model and the contraction timescale. This distinction does not affect the conclusions of the present work, as the fastness parameters of interest, both in our models and in recent observations, are smaller than those of either state.

Depending on the stellar parameters and the presence of an APSW, ZTS occurs at $0.3 \lesssim \omega_s \lesssim 1.0$ (e.g., Gehrig et al. 2025; Zhu 2025). The evolutionary timescale on which the star reaches the ZTS, τ_J , is expected to be on the order of a few million years (e.g., Lii et al. 2014; Ireland et al. 2021; Serna et al. 2024). Based on theoretical models, CTTs with ages of $\gtrsim 2$ Myr are expected to spin at (or close to) the ZTS. However, recent measurements of R_i and R_{co} have shown that a considerable number of CTTs are in a spin-up state with values of $\omega_s < 0.3$ (e.g., Thanathibodee et al. 2023; Pittman et al. 2025), which is smaller than the expected values of the ZTS (e.g., Gehrig et al. 2025). While some stars might be too young to have reached their ZTS, these observations challenge the assumption that stars evolve toward a zero torque condition.

In this work, we studied the effects of temporal variations in the stellar dipole field strength, $B_\star$, on the stellar spin evolution during the T Tauri phase of young stars. The stellar dipole field strength is an important parameter as it influences the stellar spin model (e.g., Gallet et al. 2019; Ireland et al. 2022) as well as the location of the inner disk radius (e.g., Bessolaz et al. 2008; Hartmann et al. 2016). We considered two different timescales on which $B_\star$ can change. First, the timescale τ_B over which CTTs undergo magnetic topology changes when they develop a radiative core (e.g., Gregory et al. 2012; Lavail et al. 2019). Fully convective stars tend to have magnetic field configurations that are dominated by a low-order dipole with field strengths ($B_\star$) of ~ 1 kG. As a star with a sufficient mass develops a radiative core, the magnetic field becomes more complex, with dominant high-order field components. The dipole component for these stars is up to an order of magnitude weaker: $B_\star \sim 0.1$ kG (e.g., Gregory et al. 2012). The time in which CTTs develop a radiative core depends on the stellar mass. As stated in Gregory et al. (2012), a $1 M_\odot$ star develops a radiative core after approximately 2 Myr and a $0.7 M_\odot$ star after 6 Myr, within the expected lifetime of the PPDs. The timescale on which the magnetic field adjusts to the development of the radiative core is estimated to be ~ 0.1 – 1.0 Myr (e.g., Gregory et al. 2012; Villebrun et al. 2019).

Second, we examined shorter stellar magnetic cycles, which affect $B_\star$. One mechanism that affects the stellar magnetic field is the reversal of the stellar magnetic field polarity, which can lead to a distinct change of the dipole field (like the 11-year solar cycle; e.g., DeRosa et al. 2012; Lehtinen et al. 2022; Finocietty et al. 2023b; Gaidos et al. 2024). As shown in Johnstone et al. (2014), the stellar dipole field strength can vary significantly (from 280 G to 970 G) within a time span of several years. However, we do not know if regular, well-defined stellar cycles such as the solar cycle exist in T Tauri stars. The reconstruction of the solar magnetic activity over the past few

millennia has also shown variations on longer timescales (e.g., Usoskin et al. 2021). Due to the limited data available, the applicability of such variations to T Tauri stars requires further investigation. In this work, we assumed that magnetic cycles affect the stellar dipole field in T Tauri stars on timescales of ~ 10 years. As the stellar dipole field changes over time, the inner disk and corotation radius, and thus ω_s , are affected. Starting with a star rotating in its ZTS, we modeled how a time-dependent magnetic field affects the stellar spin evolution.

2. Model description

To model the structure and long-term evolution of PPDs, we used the implicit hydrodynamic TAPIR code (e.g., Ragossnig et al. 2020; Steiner et al. 2021). The equations of hydrodynamics are combined with the description of the turbulent viscosity presented in Shakura & Sunyaev (1973). We used a layered viscosity model (Gammie 1996) featuring a low turbulent or dead zone (DZ) with a viscosity parameter α_{DZ} and a turbulent layer with $\alpha_{\text{turb}} \gg \alpha_{DZ}$. Using the TAPIR model, we could incorporate the effects of stellar magnetic torques resulting from the star–disk interaction, which cause a deviation from the Keplerian velocity within the disk, as the diffusion approach (e.g., Pringle 1981; Armitage et al. 2001) is not employed. Furthermore, the model uses an adaptive grid (e.g., Dorfi & Drury 1987), allowing the inner and outer disk boundaries to move according to variable stellar and disk parameters (e.g., the accretion rate or stellar contraction Steiner et al. 2021; Gehrig et al. 2022). In its further development, the model has been enhanced with a stellar spin model (Gehrig et al. 2022) and an X-ray photo-evaporative model (Cecil et al. 2024), in which the stellar X-ray luminosity controls the photo-evaporative mass-loss rate, L_X . As a result, the TAPIR model can combine the effects of the magnetic star–disk interaction in the innermost disk, stellar rotation, and photo-evaporation self-consistently, making it well suited for the aims of this study. We note that magnetohydrodynamic-driven disk winds are not considered in the current version of the model. The effects of such winds on the results are discussed in Sect. 4.3. We used the model as described in Cecil et al. (2024). A detailed description of the equations solved in the model and the underlying assumptions is summarized there. Here, we highlight specific aspects of the model and list the used parameters.

2.1. Calculation of the truncation radius

The inner disk or truncation radius, r_t , is calculated by equating the magnetic pressure from the stellar magnetic field, P_{mag} , and the pressure of the disk material containing the ram pressure of the accreting material, P_{ram} , and the gas pressure, P_{gas} (e.g., Koldoba et al. 2002; Romanova et al. 2002; Bessolaz et al. 2008),

$$P_{\text{mag}}(r_t) = \max[P_{\text{ram}}(r_t), P_{\text{gas}}(r_t)]. \quad (1)$$

For the case $P_{\text{ram}} \geq P_{\text{gas}}$, we followed Hartmann et al. (2016),

$$r_t(P_{\text{ram}} \geq P_{\text{gas}}) \approx 18 \xi R_\odot \left(\frac{B_\star}{10^3 \text{ G}} \right)^{4/7} \left(\frac{R_\star}{2 R_\odot} \right)^{12/7} \left(\frac{M_\star}{0.5 M_\odot} \right)^{-1/7} \left(\frac{\dot{M}_\star}{10^{-8} M_\odot/\text{yr}} \right)^{-2/7}, \quad (2)$$

where $B_\star$ is the stellar magnetic field strength, $R_\star$ the stellar radius, $M_\star$ the stellar mass, and $\dot{M}_\star$ the accretion rate on the

star, and the correction factor (ξ) is 0.7 (Hartmann et al. 2016). For $P_{\text{ram}} < P_{\text{gas}}$, the truncation radius follows from the condition

$$P_{\text{gas}}(r_t) = P_{\text{magn}}(r_t) = \frac{B_{\star}^2 R_{\star}^6}{8\pi r_t^6}. \quad (3)$$

2.2. Stellar spin model

To calculate the stellar spin evolution, we included an external torque acting on the star, $\Gamma_{\text{ext}} = \dot{J}_{\star}$, which equals the temporal derivative of the stellar AM, and the internal stellar evolution (e.g., Gallet et al. 2019). We assumed that the star rotates as a rigid body, $J_{\star} = \Omega_{\star} I_{\star}$, with the stellar moment of inertia, $I_{\star} = 0.2 M_{\star} R_{\star}^2$ (e.g., Armitage & Clarke 1996; Matt et al. 2010)¹. This results in a temporal derivative of the stellar angular velocity of

$$\dot{\Omega}_{\star} = \frac{\Gamma_{\text{ext}}}{I_{\star}} - \frac{\dot{I}_{\star}}{I_{\star}} \Omega_{\star}, \quad (4)$$

with

$$\frac{\dot{I}_{\star}}{I_{\star}} = \frac{\dot{M}_{\star}}{M_{\star}} + 2 \frac{\dot{R}_{\star}}{R_{\star}}. \quad (5)$$

The external torque consists of the effects of the accretion process, Γ_{acc} , of the APSW, Γ_{APSW} , and of the ME, Γ_{ME} ; $\Gamma_{\text{ext}} = \Gamma_{\text{acc}} + \Gamma_{\text{APSW}} + \Gamma_{\text{ME}}$ (see also Gallet et al. 2019; Gehrig et al. 2022). The accreted material carries AM that is added to the star and spins it up. An APSW removes AM from the star and causes a spin-down effect. MEs can spin up or spin down the star depending on the value of ω_S . In the model of Gallet et al. (2019), MEs spin up the star for $\omega_S \leq 0.7$.

Following Matt et al. (2010), the star contracts along the Hayashi track on its Kelvin-Helmholtz timescale², resulting in a radius change according to

$$\dot{R}_{\star} = 2 \frac{R_{\star}}{M_{\star}} \dot{M}_{\star} - \frac{28\pi\sigma R_{\star}^4 T_{\text{eff}}^4}{3GM_{\star}^2}, \quad (6)$$

where T_{eff} is the stellar effective temperature and σ the Stefan-Boltzmann constant. A detailed summary of the respective equations can be found in our previous work (Gehrig et al. 2022) and in Gallet et al. (2019).

2.3. Variable magnetic field

We studied the effects of a time-dependent magnetic field strength on two different timescales. First, the long-term effect of a decrease in the stellar dipole field strength due to the development of a radiative core was simulated (called the “long model”). According to Gregory et al. (2012), fully convective T Tauri stars host magnetic fields with a dominant dipole component of $B_{\star} \gtrsim 1$ kG. Stars that have developed radiative

cores, on the other hand, show more complex fields with dominant higher-order field components and weaker dipole fields of $B_{\star} \sim 0.1$ kG. Recent observations suggest that different dynamo mechanisms are responsible for generating the magnetic field in fully convective and partially convective stars (e.g., See et al. 2025), with notable differences particularly in the large-scale or dipole field strengths. It is assumed that the dipole component is the dominant component controlling the star–disk interaction (e.g., Finley & Matt 2018). The transition between these two states should occur within a few tenths of a megayear (e.g., Gregory et al. 2012; Villeda et al. 2019). In our model, we started with a stellar dipole field of $B_{\star} = 1$ kG at the beginning of the simulations. The initial stellar age, t_{init} , corresponds to the development of the radiative core and depends on the stellar mass (see Sect. 2.4 and Table 1). After a simulation time of $\tau_0 = 10^4$ years, $B_{\star}$ decreases and reaches 0.1 kG after $\tau_B = 0.5$ Myr (see panel a of Fig. 1).

Second, we included short-term variations due to stellar cycles (e.g., Armitage 1995, referred to as the “short model”). During a cycle period of τ_{cyc} , the stellar field strength varies according to

$$B_{\star}(t) = B_{\text{mean}} + B_{\text{osc}} \sin\left(\frac{2\pi t}{\tau_{\text{cyc}}}\right), \quad (7)$$

where B_{mean} is the mean dipole field component and B_{osc} the oscillating field component. Again, we started with the variation of $B_{\star}$ after $\tau_0 = 10^4$ years. In fact, measurements of stellar dipole fields show a strong variability of $B_{\star}$ over several years. For example, the dipole field of V2129 Oph has increased from 280 G in 2005 to 970 G in 2009 (Johnstone et al. 2014). Based on the variation in photometric data of T Tauri stars ranging on timescales of 1.5–4 years (e.g., Lin et al. 2023), the cycle timescale can be estimated to be around ~ 3 years (e.g., Gaidos et al. 2024). Furthermore, models of cool dwarfs (e.g., Bice & Toomre 2023) and solar-like stars (e.g., Strugarek et al. 2018) suggest plausible cycle timescales of ~ 1 year and ~ 30 years, respectively. Thus, we chose $\tau_{\text{cyc}} = 10$ years (following Armitage 1995), $B_{\text{mean}} = 1.0$ kG, and $B_{\text{osc}} = 0.9$ kG. An illustration of $B_{\star}(t)$ is given in Fig. 1b. Short-term variations of the stellar magnetic field of T Tauri stars are associated with a polarity reversal of the magnetic field (similar to the 11-year solar cycle; e.g., DeRosa et al. 2012; Finocciety et al. 2023b; Gaidos et al. 2024). We note that the adopted form of the short-term magnetic cycle (Eq. 7) corresponds to an “effective” or absolute dipole field component acting on the disk. During a polarity reversal, the dipole field would decrease toward zero and change sign (as recently reported in Donati et al. 2026). For a dipole field close to zero, field components of higher order (quadrupole or octopole fields) start to affect the disk, resulting in an effective, nonzero component even at the polarity inversion (e.g., Finley & Matt 2018). In addition, we assumed that the alignment between the dipole field and the disk’s rotational axis is fixed. We discuss additional effects due to the changing alignment between the magnetic and rotational axes in Sect. 4.4. Further, the sinusoidal form of the cycle (following Armitage 1995) is an approximation. Observed magnetic field intensities in young stars show rather abrupt changes in the dipole component during possible polarity reversals (e.g., Finocciety et al. 2023b). Although the exact form of the cycle remains unclear, the results of this work should not be significantly affected by a different cycle form. We chose the sinusoidal representation for its numerical stability.

¹ A developing radiative core in a young star eventually decouples from the convective envelope. However, the timescale at which the core rotation diverts significantly from the envelope is assumed to be on the order of $\gtrsim 10$ Myr (e.g., Gallet & Bouvier 2013), which is older than most T Tauri systems. Thus, the assumption of rigid stellar rotation should be valid within the scope of this study.

² This assumption is usually used to describe fully convective stars. However, the stellar radius evolution described here does not deviate significantly from stellar evolution tracks (e.g., Baraffe et al. 2015) within the first ~ 10 Myr for stellar masses of $M_{\star} \lesssim 1.0 M_{\odot}$.

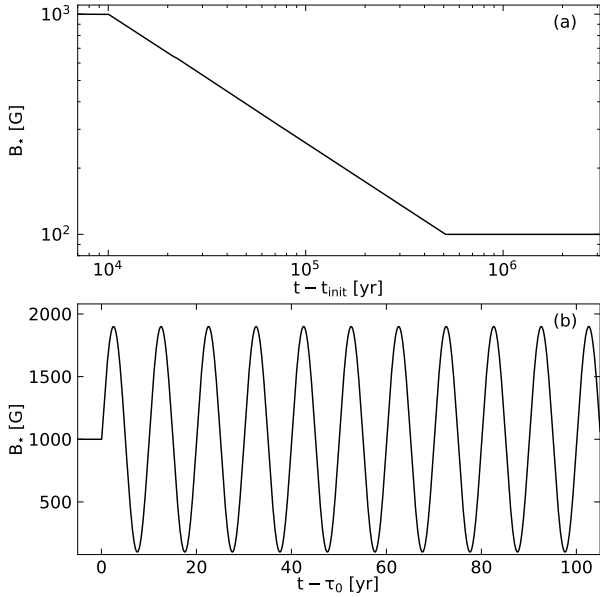


Fig. 1. Illustration of the time-dependent dipole field strength used in this work. Panel a: Long-term evolution due to the development of a radiative core. Panel b: Short-term variation due to stellar cycles.

2.4. List of parameters

Here, we provide an overview (see Table 1) of the parameters used in this work. We modeled three different stellar masses. To study the effects of a developing radiative core, we chose $M_{\star} = 1.0$ and $0.7 M_{\odot}$. According to stellar evolution models, a solar mass star develops a radiative core shortly after 2 Myr and a $0.7 M_{\odot}$ star at around 5 Myr (e.g., Siess et al. 2000; Tognelli et al. 2011), which is the assumed stellar age at the beginning of the respective simulations, t_{init} . Magnetic cycles are also modeled for these stars, and, in addition, for a $0.3 M_{\odot}$ star with an initial age of 2 Myr. The initial stellar radii for the respective stars are based on isochrone models from Baraffe et al. (2015), and the initial accretion rates are chosen to be within the observed range reported in Betti et al. (2023). The viscosity parameters are taken from Cecil et al. (2024); $\alpha_{\text{turb}} = 0.02$ and $\alpha_{\text{DZ}} = 0.0004$. The initial rotation periods correspond to the respective ZTS ($\Gamma_{\text{ext}} \approx 0$) assuming an APSW efficiency of $W = 1\%$ and $B_{\star, \text{init}} = 1.0$ kG. The fastness parameter of the ZTS resulting from these input values is $\omega_S \approx 0.72$, which matches the results of recent simulations (Zhu 2025) and population models (Gehrig et al. 2025). We initialized at ZTS rather than at spin equilibrium to isolate the effect of the variable magnetic field. We note that the star will spin up from stellar contraction in this configuration. Finally, we needed to choose the stellar X-ray luminosity, which is responsible for the photo-evaporative mass-loss. Recent developments in photo-evaporative models have shown lower mass-loss rates (by up to one order of magnitude) due to enhanced cooling (e.g., Sellek et al. 2024) compared to previous models (e.g., Ercolano et al. 2021). To get a mass-loss rate in our models that is comparable to the results presented in Sellek et al. (2024), we reduced the X-ray luminosities from Güdel et al. (2007) by a factor of 20.

3. Results

Before analyzing the evolution of the long and short models, we wanted to compare the relevant evolution timescales for the

Table 1. Initial model parameters used in this work.

$M_{\star, \text{init}} [M_{\odot}]$	1.0	0.7	0.3
$t_{\text{init}} [\text{Myr}]$	2.0	5.0	2.0
$R_{\star, \text{init}} [R_{\odot}]$	1.917	1.243	1.238
$T_{\text{eff}} [\text{K}]$	4350	3960	3428
$L_X [\text{erg/s}]$	1×10^{29}	5×10^{28}	1×10^{28}
$\dot{M}_{\star, \text{init}} [M_{\odot}/\text{yr}]$	10^{-8}	3×10^{-9}	2×10^{-9}
$P_{\star, \text{init}} [\text{days}]$	4.2	3.0	6.0

star–disk system (see Fig. 2). In the inner disk, the truncation radius adjusts on the order of days, equivalent to the dynamic timescale, $\tau_{\text{dyn, in}} \sim \text{days}$ (e.g., Pittman et al. 2025), and the accretion rate evolves on the viscous timescale, $\tau_{\text{v, in}} \sim 1000$ years. The viscous timescale in the outer disk, $\tau_{\text{v, out}} \sim 9 \times 10^5$ years, is a measure for the long-term evolution of the disk accretion rate and the disk lifetime. The stellar spin evolves on a timescale $\tau_{\text{spin}} \equiv \Omega_{\star}/\dot{\Omega}_{\star}$ that combines the effect of the external torques and of stellar contraction. Neglecting the slow change of the stellar mass, Eqs. (4)–(6) yield

$$\tau_{\text{spin}} = \frac{\tau_J \tau_{\text{KH}}}{\tau_{\text{KH}} + 2 \tau_J}, \quad (8)$$

where $\tau_J = J_{\star}/|\dot{J}_{\star}|$ is the timescale associated with the external (accretion + spin-down) torques and $\tau_{\text{KH}} = R_{\star}/|\dot{R}_{\star}|$ is the Kelvin-Helmholtz timescale set by the second term on the right-hand side of Eq. (6). The external-torque timescale τ_J is not constant: it can reach $\sim (1-2) \times 10^6$ yr in the spin-down regime at large fastness parameters (e.g., Ireland et al. 2022), but becomes considerably shorter in an accretion-dominated spin-up regime. For our initial conditions, the system starts in a ZTS ($\tau_J \rightarrow \infty$), and τ_{spin} is set by contraction, $\tau_{\text{spin}} \approx \tau_{\text{KH}}/2$ of approximately a few megayears. Once the simulation starts and the value of $B_{\star}$ changes, the star moves out of the ZTS, and τ_J becomes variable. During our simulations, τ_{spin} stays at values of $\gtrsim \tau_{\text{v, out}}$. Depending on the relation between these timescales and $\tau_B = 5 \times 10^5$ years and $\tau_{\text{cyc}} = 10$ years, we expect different reactions of the disk on the variation of $B_{\star}$. Since $\tau_B \gg \tau_{\text{v, in}} \gg \tau_{\text{dyn, in}}$, we expect that the inner disk quickly adjusts to magnetic variations due to a growing radiative core. The long-term evolution of the disk and the stellar rotation period, on the other hand, should only slowly adjust to the new magnetic field strength as $\tau_B < \tau_{\text{v, out}} < \tau_{\text{spin}}$. In the case of magnetic cycles, the viscous timescales in the disk and the stellar spin evolution timescale are slow to react to the short-term changes in $B_{\star}$. The position of the truncation radius, however, should adjust to the variations quickly. Thus, we can expect a nontrivial reaction in the inner disk due to the short magnetic cycles. Overall, the stellar spin evolution (and the position of the corotation radius) is slow to react to changes in the magnetic field, and the truncation radius adjusts quickly. Thus, we expect the stellar spin state, defined by the fastness parameter ω_s , to be directly affected by a variable $B_{\star}$.

We started our simulations with a star in the ZTS with a fastness parameter of $\omega_S \approx 0.72$. After $\tau_0 = 10^4$ years, the temporal variation of $B_{\star}$ begins. In Fig. 3, the results for the long model are shown for stellar masses of 1.0 and $0.7 M_{\odot}$. For comparison, we include simulations in which the magnetic field remains constant. With a decrease in $B_{\star}$ after $\tau_0 = 10^4$ years, the truncation radius decreases according to Eq. (2) almost instantly on a timescale $\tau_{\text{dyn, in}}$ (panel b). The stellar rotation period and

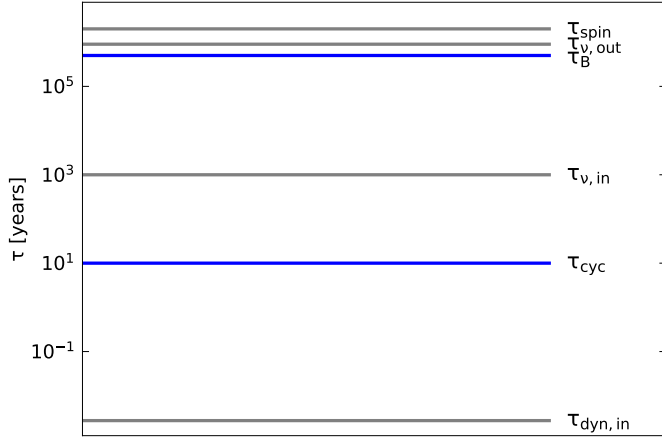


Fig. 2. Evolution timescales of the star-disk system relevant for this work. The timescales on which the magnetic field is assumed to change are marked in blue.

the corotation radius remain approximately constant as the stellar spin evolves on a larger timescale τ_{spin} (see Fig. 2). Consequently, the fastness parameter decreases from its initial value of 0.72 toward ≈ 0.17 (or by a factor of ≈ 4). As long as the accretion rate remains above $\dot{M}_\star \gtrsim 10^{-9} M_\odot \text{ yr}^{-1}$, the stellar spin slowly adjusts to the new condition, the star spins up, and ω_s increases over the next few million years. As the accretion rate decreases due to viscous evolution and PE, the truncation radius increases, ultimately resulting in a value of $\omega_s \approx 1$ as the accretion rate drops toward zero. During their T Tauri lifetime, stars at different masses ($M_\star \gtrsim 0.7 M_\odot$) start to develop a radiative core at different ages, and for all these different stellar masses, observations show a significant scatter in accretion rates. As a result, numerous combinations of stellar masses, ages, and accretion rates yield different rotation periods in their respective ZTS. For both stellar masses, which are shown here at different ages, the effect of a decreasing dipole field strength due to the development of a radiative core is similar.

In the case of stellar magnetic cycles, the corresponding timescale $\tau_{\text{cyc}} = 10$ years is significantly smaller than the stellar or disk evolution timescales. Thus, we assumed that the stellar radius remains constant over several τ_{cyc} . In contrast to the development of a radiative core, stellar magnetic cycles can also affect smaller stars that remain fully convective during their disk phase. The evolution of the short model for three different stellar masses, ages, and accretion rates is shown in Fig. 4. With an increasing magnetic field strength, the truncation radius is pushed away from the star (see Eq. (2)). The disk material cannot adjust to the change in the truncation radius as the viscous timescale in the inner disk is significantly larger compared to the cycles timescale ($\tau_{\text{v,in}}/\tau_{\text{cyc}} \gtrsim 100$). As a consequence, more disk material is located inside r_t and is accreted on the star, increasing the accretion rate (panel a). Similarly, as $B_\star$ decreases, the disk material cannot follow the decreasing truncation radius, and the accretion rate also decreases. We note that for all our simulations the condition $r_t < R_{\text{co}}$ or $\omega_s < 1$ is fulfilled. Should the increase in magnetic field strength push the truncation radius beyond the corotation radius, disk material would be propelled away from the star and the accretion rate would significantly drop (e.g., Armitage 1995; Romanova et al. 2004a). The slow back-reaction in the accretion rate ($\tau_{\text{v,in}} > \tau_{\text{cyc}}$) weakens the effect of the magnetic cycles on the ZTS (the change in the accretion rate has an opposite effect on r_t compared to the variable magnetic field,

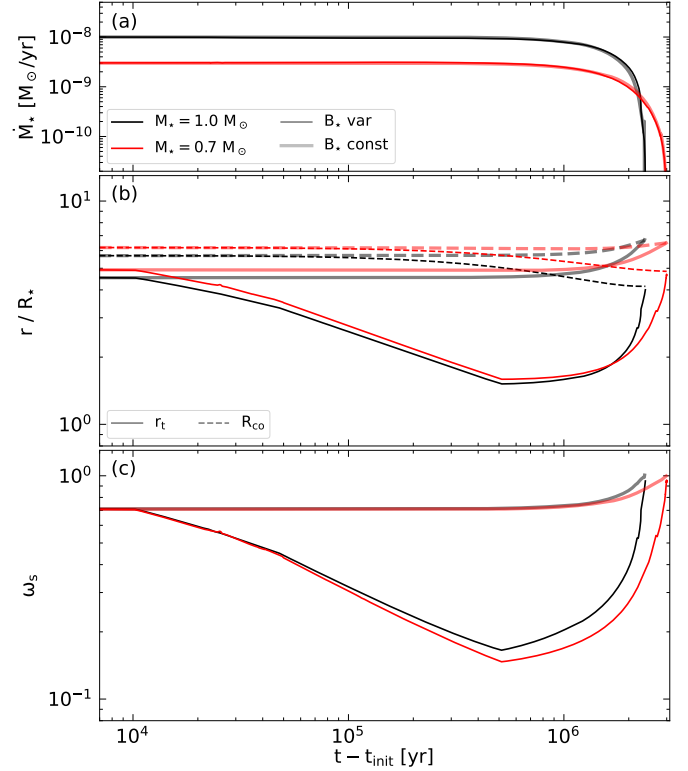


Fig. 3. Evolution of the long model compared to simulations with a constant magnetic field strength. The initial stellar ages of the 1.0 and $0.7 M_\odot$ models are $t_{\text{init}} = 2.0$ and 5.0 Myr (see Table 1), respectively. Panel a: Accretion rate. Panel b: Truncation radius, r_t , and the corotation radius, R_{co} , in units of the stellar radius. Panel c: Fastness parameter, ω_s .

panel c and Eq. (2)). During one cycle, ω_s varies between 0.87 and 0.50 (or by a factor of 1.74). Although the absolute values vary, the overall behavior of the accretion rate and ω_s is comparable for the different stellar masses, ages, and accretion rates.

4. Discussion

4.1. Comparison with observations

Recently, the truncation radius of T Tauri stars has been derived from observational data in combination with the stellar rotation period and the corotation radius for a few dozen stars (Thanathibodee et al. 2023; Pittman et al. 2025). In both cases, a significant number of stars show values ω_s smaller than expected from stellar spin models (e.g., Ireland et al. 2022; Serna et al. 2024; Zhu 2025). Based on the results presented in Pittman et al. (2025), we wanted to compare the ω_s values of fully convective stars and stars that have started to develop a radiative core. For this comparison, we selected stars with stellar masses of $M_\star \gtrsim 0.7 M_\odot$ (see Table 2). For these stellar masses, the radiative core is expected to develop within the first 5 Myr of their lifetimes. For each star, we compared the stellar age taken from the literature with the end of the fully convective phase τ_{conv} based on the stellar evolution models of Tognelli et al. (2011, see also Gregory et al. 2012).

$$\tau_{\text{conv}} [\text{Myr}] \approx \left(\frac{1.448}{M_\star/M_\odot} \right)^{2.101}. \quad (9)$$

We note that a minimum value of ω_s should be reached at around $\tau_B = 0.5$ Myr after the radiative core starts to develop

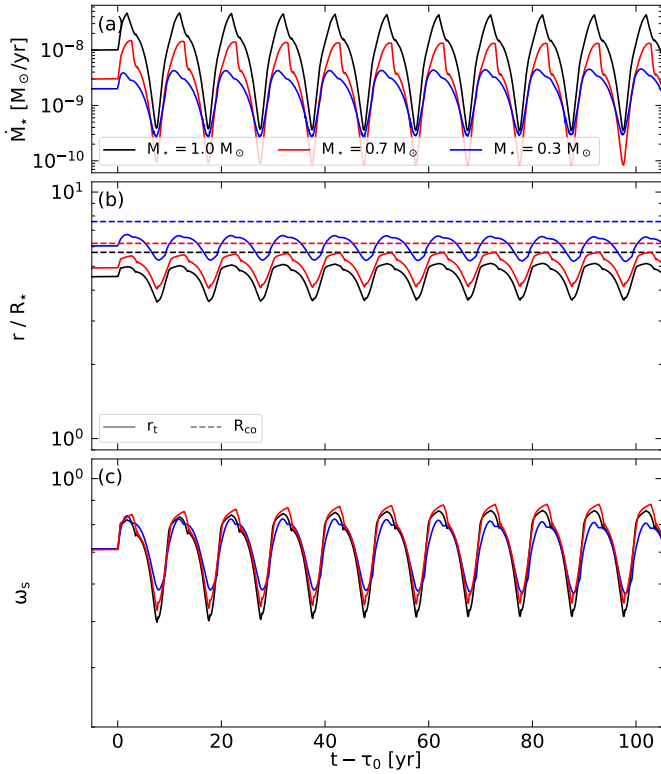


Fig. 4. Evolution of the short model. The panels are the same as in Fig. 3. The time reference is the beginning of the magnetic cycles at a simulation time of $\tau_0 = 10^4$ years.

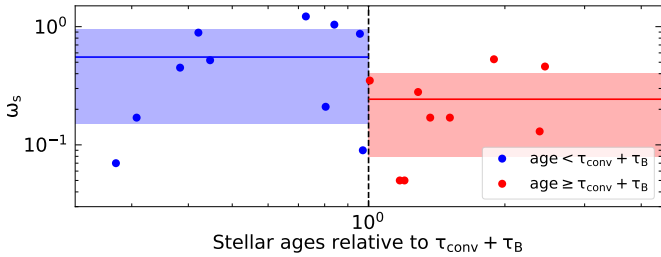


Fig. 5. Comparison of the values of ω_s of the young (ages $< \tau_{conv} + \tau_B$) and old (ages $\geq \tau_{conv} + \tau_B$) stars listed in Table 2. The stellar ages are plotted relative to $\tau_{conv} + \tau_B$ (marked by the vertical dashed line). The horizontal lines show the respective mean values, and the colored areas mark the respective standard deviations.

(see Fig. 3). For a $1.0 M_\odot$ star, this results in a stellar age of $\tau_{conv} + \tau_B \approx 2.6$ Myr and for a $0.7 M_\odot$ star, in an age of $\tau_{conv} + \tau_B \approx 5.1$ Myr according to Eq. (9). We distinguish between stars with ages older (“old” stars) and younger (“young” stars) than $\tau_{conv} + \tau_B$ and compare the values of ω_s in Fig. 5. For young stars, the mean fastness parameter is $\omega_s = 0.55 \pm 0.40$ and for old stars, $\omega_s = 0.24 \pm 0.16$. The values for young stars are consistent with the ZTS for a spin model including an APSW (see Gehrig et al. 2025). The values for old stars match the simulation results shown in Fig. 3b.

While this initial comparison suggests an age trend in ω_s , we note that some caution remains warranted. First of all, the small number of available observations and the resulting uncertainties require more measurements to draw a clear conclusion. The two stars with the largest values of ω_s , MY Lup and CV Cha, are in the regime $\tau_{conv} < \text{age} < \tau_{conv} + \tau_B$. According to Fig. 3,

some initial effects of the decreasing dipole field component on ω_s should already be noticeable. Although this dataset is not fully consistent with the results presented in this work, the observational uncertainties should be taken into account. The inner disk radius and, in turn, ω_s are subjected to short-term variability, for example, due to variability in the accretion rate (e.g., Zsidi et al. 2022; Robinson et al. 2022). In the case of MY Lup, the value of ω_s varies from 0.55 to 1.42 during the observations (Pittman et al. 2025). Further, mass and age estimates can vary significantly depending on the observation method itself (e.g., Flores et al. 2022). For example, the age of CV Cha is reported to be 1.3–1.5 Myr (from which the mean value was used in Table 2; Ginski et al. 2024) and 3.0–4.5 Myr (Gregory et al. 2012). Another potential source of uncertainty in stellar age estimates is the disk itself. A large inclination (as in the case of MY Lup) and flaring can extinct the host star, leading to an overestimation of the stellar age (e.g., Andrews et al. 2018). As a result, the age of MY Lup has been corrected from 16.6 Myr, as reported in Frasca et al. (2017), to 2 Myr (Long et al. 2022). In addition, the effects of binaries and magnetic stellar evolution models (e.g., Feiden 2016) are not included in this preliminary comparison.

We further note that the value of ω_s should increase again due to decreasing accretion rates toward the end of the disk’s lifetime (see Fig. 3). For all but two stars from the sample of Pittman et al. (2025), the accretion rate shows values of $\dot{M}_* > 10^{-9} M_\odot \text{yr}^{-1}$ even at older ages, and small values of ω_s are expected after the radiative core has formed, matching our results. The accretion rates provided by Thanathibodee et al. (2023), on the other hand, range at $\dot{M}_* \sim 10^{-10} M_\odot \text{yr}^{-1}$ and they find values of $\omega_s \lesssim 0.45$ for most stars in their study, contradicting our results. As discussed in Thanathibodee et al. (2023), the mechanisms that shape the final stages of disk accretion in T Tauri stars have to be studied in future work. However, analyzing the stellar spin state (e.g., by means of the fastness parameter) at different stellar evolutionary stages (e.g., age $< \tau_{conv}$, age $\approx \tau_{conv}$, and age $> \tau_{conv}$) can advance our understanding of the star–disk interaction. One mission that could provide the fastness parameter for many stars is the Early eVolution Explorer (EVE) satellite (MacGregor et al. 2025). With a combined derivation of the truncation radius, the accretion rate, and the stellar rotation period, EVE can increase the available data by a factor of ≥ 15 .

Comparing our results on magnetic cycles with observational data proves to be no less challenging. While variation in the dipole field strengths on the timescales of years have been known for a few stars (e.g., Johnstone et al. 2014; Finociety et al. 2023a; Gaidos et al. 2024), the first magnetic polarity reversal of a T Tauri star has been reported recently (for the star DO Tau, see Donati et al. 2026). A suitable comparison with our results requires simultaneous measurements of the dipole field strength, the truncation radius (that can be calculated with the accretion rate and the dipole field strength Bessolaz et al. 2008; Hartmann et al. 2016), and the stellar rotation period (setting the corotation radius). The SpectroPolarimetre InfraRouge (SPIRou) Legacy Survey does provide these measurements (e.g., Donati et al. 2020, 2024, 2026). In the course of the survey, young, accreting stars show variations of the dipole field strengths on timescales of several years. The dipole strength of V1298 Tau decreases from 245 G to 85 G (a factor of almost 3) during one year (Finociety et al. 2023a) and during the polarity reversal of DO Tau, the dipole field evolves from -190 G to 320 G (Donati et al. 2026). The absolute change of the dipole field in these stars is relatively small (~ 100 G) compared to the

Table 2. Mean stellar parameters from Pittman et al. (2025), including stellar ages taken from the literature.

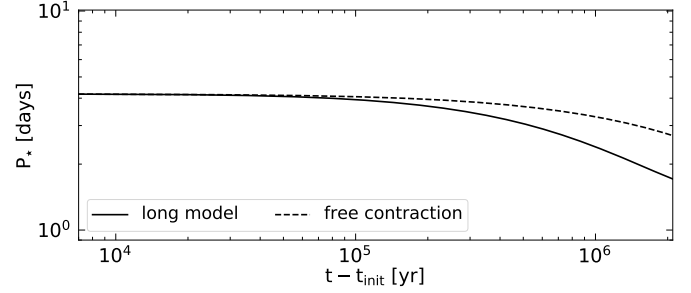
Name	Mass [$M_{\odot}$]	ω_s	Age [Myr]	Age class	Age ref
MY Lup	1.06	1.22	2.0	y	1
CV Cha	1.40	1.04	1.4	y	2
CVSO 58	0.81	0.89	2.0	y	3
Sz 19	2.37	0.87	0.8	y	2
CS Cha	1.22	0.53	4.0	o	2
Sz 68	1.83	0.52	0.5	y	4
RX J1842.9 –3532	1.04	0.46	10	o	5
TX Ori	1.09	0.45	1.0	y	6
UX Tau A	1.50	0.35	1.5	o	7
V510 Ori	0.76	0.28	7.0	o	8
SZ Cha	1.22	0.21	1.7	y	2
AA Tau	0.80	0.17	1.5	y	9
RX J1852.3 –3700	0.82	0.17	10	o	5
V505 Ori	0.81	0.17	6.5	o	8
CVSO 146	0.86	0.13	10	o	6
RECX 11	0.78	0.09	5.0	y	10
SY Cha	0.70	0.07	1.8	y	2
RY Lup	1.40	0.05	2.0	o	11
J160830.7 –382827	1.38	0.05	2.0	o	12

Notes. The column “Age class” corresponds to young (y) and old (o) stars with respect to $\tau_{\text{conv}} + \tau_B$. Age references: (1) Long et al. (2022), (2) Ginski et al. (2024), (3) Pittman et al. (2022), (4) Frasca et al. (2017), (5) Roccatagliata et al. (2009), (6) Valegård et al. (2024), (7) Ménard et al. (2020), (8) Maucó et al. (2016), (9) Donati et al. (2010), (10) Rugel et al. (2018), (11) GRAVITY Collaboration (2020), and (12) Biazzo et al. (2017).

present study and effects on the accretion rate are not clearly measurable. Larger dipole variations are reported for V2129 Oph from 280 G in 2005 to 970 G in 2009 (Johnstone et al. 2014). Unfortunately, the accretion rates have not been measured simultaneously and the effect of the different dipole field strengths on the accretion rate, the truncation radius, and the stellar spin state cannot be estimated. Future results by surveys like SPIRou will provide valuable data for constraining stellar magnetic cycles and their effects on the stellar spin evolution.

4.2. Other factors affecting the stellar spin state

During the evolution of a T Tauri star, other factors can affect the stellar spin state through the truncation radius or the corotation radius. In terms of the truncation radius, the most volatile contributing factors are the magnetic field strength and the accretion rate (see Eq. 2). The accretion rate can be variable on timescales of days to years (see the review by Fischer et al. 2023). Observations show a routine variability of <1 – 2 mag over days to years (matching the dynamic and viscous timescale of the inner disk; e.g., Cody et al. 2017). In addition, outburst events can increase the accretion rate by up to 6 mag and can last for years to decades (e.g., Fu Ori outbursts; Kóspál et al. 2011). While we have observed a back-reaction of the accretion rate on the stellar magnetic cycles, there are other reasons for a variable $\dot{M}_{\star}$ that are independent of $B_{\star}$ (e.g., Fischer et al. 2023). According to Eq. (2), a one-order-of-magnitude increase in the accretion rate

**Fig. 6.** Evolution of the stellar rotation period of the long model for a stellar mass of $1.0 M_{\odot}$. The rotation period of a contracting star according to Eq. (6) without any external torque contributions is shown for comparison.

will push the truncation radius inward by a factor of 0.52, corresponding to a decrease in ω_s by 63%. Together with the effect of a stellar magnetic cycle, the value of ω_s can be decreased even further. The potential combination of these effects could lead to a significant deviation from the ZTS.

Another factor that can affect the stellar spin state of observed stars is the assumed spin model itself. The ZTS value of ω_s varies with different spin models, as the torque contributions acting on the star are subject to change with theoretical and observational advances (e.g., Ireland et al. 2021, 2022; Takasao et al. 2025; Zhu 2025). In their 3D model, for example, Takasao et al. (2025) found that MEs might play only a minor role in the stellar spin evolution, whereas CDWs can potentially remove significant amounts of disk and stellar AM (comparable to a strong APSW). An additional torque contribution that removes stellar AM, similar to an APSW, can result in smaller ω_s values in the ZTS (Gehrig et al. 2025). Unfortunately, these recent models are restricted to a limited parameter space due to high computational costs (e.g., Takasao et al. 2022; Zhu 2025), and generalizing the results might not be straightforward.

This apparent incompleteness of the stellar spin model can be illustrated by the evolution of the stellar rotation period. In Fig. 6 we show the rotation period of the long model for a stellar mass of $1.0 M_{\odot}$ (see also Fig. 3). For comparison, the stellar rotation period of a contracting star according to Eq. (6) without any external torque contributions is highlighted. With a decreasing stellar magnetic field strength and low values of ω_s , a spin-up torque is exerted onto the star in addition to its contraction, leading to fast rotation periods. This spin-up contradicts the observed constancy of rotational distributions (e.g., Smith et al. 2023), which indicates that certain spin-down contributions are not yet completely covered by the stellar spin model, as stated above, for example, the effects of winds in the innermost disk region.

4.3. Dependence on timescales

We have shown the effects of a variable $B_{\star}$ based on two different scenarios acting on two different timescales. These timescales, however, might vary according to different stellar masses or ages. First, we show how the long model reacts if we change τ_B to 10^5 years and 2×10^6 years. The stellar spin reacts to a changing magnetic field strength on timescales of $\tau_{\text{spin}} \gtrsim 2$ – 3 Myr (see Fig. 3). If the timescale on which the magnetic field changes is significantly smaller, $\tau_B \ll \tau_{\text{spin}}$, the stellar spin cannot adjust to the new parameters and the relative effect on ω_s is large (blue lines in Fig. 7). For increasing values of

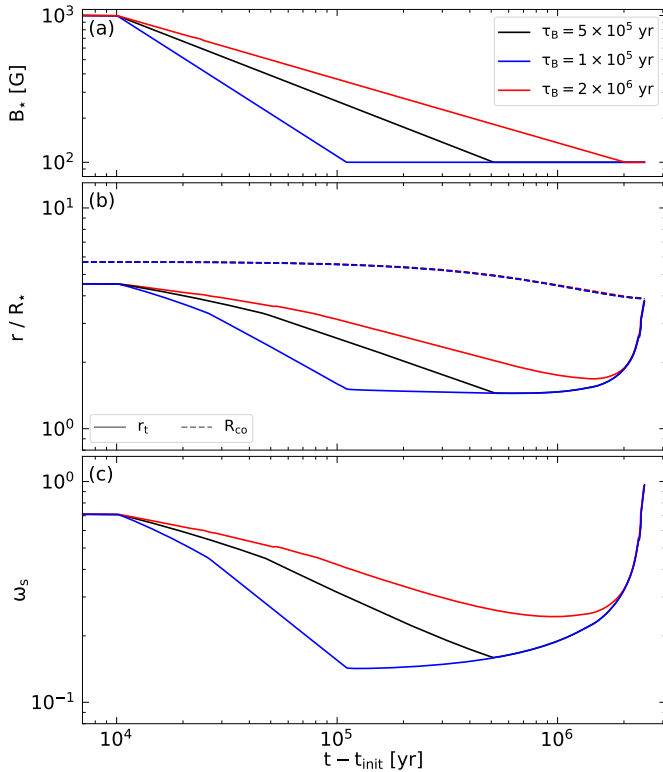


Fig. 7. Effect of different values of τ_B on the long model. The stellar mass is $1.0 M_\odot$. Panel a: Dipole field strength, B_* . Panels b and c: Same as in Fig. 3.

$\tau_B \sim \tau_{\text{spin}}$, the stellar spin can be adjusted to the changing parameter, and the relative effect on ω_s is weaker (red lines in Fig. 7). If τ_B were much larger than τ_{spin} , we would not expect a significant shift away from the ZTS. In addition to the adjustment of the stellar spin to the new magnetic field strength, the decrease in the accretion rate due to the disk evolution and PE can limit the effect on ω_s in the case of large values of τ_B .

For variations in magnetic field strength on shorter timescales, we show how different values of τ_{cyc} affect the evolution of ω_s (see Fig. 8). As shown in Fig. 4, the disk material is slow to adjust to variations shorter than the viscous timescale in the inner disk ($\tau_{\text{cyc}} < \tau_{\text{v, in}} \approx 1000$ years, black lines). As a result, the accretion rate is affected by the magnetic cycle (the variable accretion rate has an opposite effect on r_t compared to the variable magnetic field), and the effect on ω_s is weakened. For increasing values of $\tau_{\text{cyc}} = \tau_{\text{v, in}}$, the disk material can adjust to the magnetic field variation, and enough disk material can be redistributed within the inner disk. As a result, the effect of a variable magnetic field on the accretion rate becomes smaller for increasing values of τ_{cyc} , and the accretion rate remains closer to its initial value. Thus, the ω_s is shifted further away from its ZTS (blue lines). For even larger values $\tau_{\text{v, in}} < \tau_{\text{cyc}} = 10^4$ years, ω_s is pushed toward values of ~ 0.2 (red lines)³. While ω_s is shifted significantly toward smaller values as a result of a decreasing field strength during a magnetic cycle, the shift toward larger values is weaker. When the truncation radius is pushed outward by an increasing magnetic field, the disk pressure increases close

to the corotation radius (e.g., Steiner et al. 2021; Ireland et al. 2022), preventing a further outward shift. Summarizing, the effect of short-term magnetic variations on ω_s depends on the relation between τ_{cyc} and the viscous timescale of the inner disk $\tau_{\text{v, in}}$. A shift of the disk's inner radius toward the star will also increase the temperature structure of the innermost disk regions. If the temperature increase is sufficient to ionize enough disk material, magneto-rotational instabilities can be triggered, causing further variability. These effects, however, are beyond the scope of this work and might be the subject of future studies.

As mentioned in Sect. 2, the current model does not include the effects of magnetohydrodynamic-driven disk winds. There is growing theoretical and observational evidence that disk winds are essential for the evolution of PPDs (e.g., Zhu & Stone 2018; Jacquemin-Ide et al. 2021; Pascucci et al. 2023; van Dishoeck et al. 2025; Zhu 2025; Feeney-Johansson et al. 2026). Within the context of the present work, we want to discuss the effect of such disk winds on our results. The effect of a variation in the stellar magnetic field on the spin state depends on how fast the disk can react to changes in field strength. In a disk evolution scenario dominated by magnetohydrodynamic winds, the accretion timescale, τ_{acc} , is expected to be shorter compared to the viscous timescale. Models yield estimates of around $\tau_{\text{acc}} \sim 100 \times \tau_{\text{dyn}}$ (e.g., Jacquemin-Ide et al. 2021). In the outer disk regions, this is comparable to the viscous timescale (see also Tabone et al. 2021), and our results should also apply to the wind-driven scenario. In the inner disk, on the other hand, the accretion timescale is significantly shorter than the viscous timescale, $\tau_{\text{acc}} \lesssim \tau_{\text{cyc}} \ll \tau_{\text{v, in}}$ (see also Fig. 2). As a result, material in the inner disk would react more quickly, and the stellar spin state should become more sensitive to variations in the stellar magnetic field strength (this would be comparable to larger values of τ_{cyc} in Fig. 8). The precise effects of disk winds on the stellar spin state will be the subject of future studies of this model, extended with magnetohydrodynamic-driven winds (with the fundamentals already included in Steiner et al. 2025).

4.4. Further implications for the inner disk

In this work, we did not include the large-scale disk magnetic field (for recent developments we refer to Steiner et al. 2025) or the effects resulting from the reversal of the magnetic field's polarity (see Sect. 2.3). However, the stellar magnetic field can dominate the large-scale magnetic field topology in the inner disk region (see Steiner et al. 2025). Recent 3D simulations of the star-disk connection have shown that only a very limited region of the disk is directly connected to the star ($r \lesssim R_{\text{co}}$; e.g., Takasao et al. 2022; Zhu 2025). Stellar field lines threading the disk at larger radii open up and are not able to transfer AM between the star and the disk. However, a changing polarity of the stellar magnetic field has implications on the resulting magnetic field strength and wind launching mechanisms (e.g., Ferreira et al. 2006) in the very inner disk:

- (i) In the anti-aligned case, magnetic flux, transported inward by magnetic advection, builds up close to the inner disk region, where the stellar magnetic field is strong enough to support closed field lines. This leads to an increased magnetic field strength in the vicinity of the magnetic truncation radius. In this configuration, an out-bursting, reoccurring outflow (for example, MEs) can transport AM between the star and the disk (e.g., Romanova et al. 2009; Zanni & Ferreira 2013).
- (ii) In the aligned case, the magnetic flux can merge/reconnect with the stellar magnetic field. At the point, where the

³ We note that large values of $\tau_{\text{cyc}} \gtrsim 100$ years are yet to be confirmed for T Tauri stars. Based on ice-core reconstructions, Vonmoos et al. (2006) found variations in solar activity ranging around 10^3 – 10^4 years that might also be applicable for younger stars.

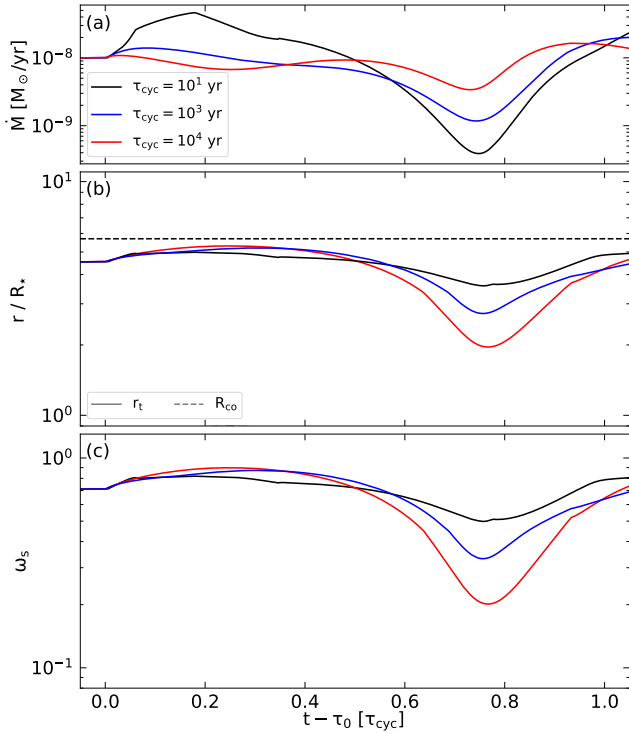


Fig. 8. Effect of different values of τ_{cyc} on the short model. The stellar mass is $1.0 M_{\odot}$. The time axis is normalized to one cycle, starting at τ_0 . The panels are the same as in Fig. 3.

stellar field “cancels out” the disk field (the so-called X-point), open field lines can connect to the closed stellar field lines and remove AM (e.g., Ferreira et al. 2000).

An oscillating polarity therefore likely leads to a time-dependent change in magnetic field strength and field topology close to the inner disk rim. This has an impact on the possibility and strength outflows originating from the innermost disk region (e.g., Lesur et al. 2023). Thus, periodically changing stellar fields could be a possible source of time-dependent disk winds. Recent observations of disk outflows and jets show “knotty” jets, which could be caused by a change in the magnetic field polarity (e.g., Vorobyov et al. 2018; Bajaj et al. 2025). To study the effects of changing magnetic field polarity on the inner disk and winds, future models should combine: (i) the innermost disk region including the magnetic star-disk connection, (ii) a description of the large-scale magnetic field, and (iii) a wind model, describing the launch of magneto-centrifugal and magneto-thermal winds.

5. Summary

In this work we show that the temporal variation of the stellar dipole field strength ($B_{\star}$) can have a distinct effect on the stellar spin state, described by the fastness parameter (ω_s). Observations have shown significantly lower values of ω_s than expected from stellar spin models. Two potential scenarios of a variable magnetic field have been studied. First, the decrease in $B_{\star}$ due to the development of a radiative core on a timescale of $\tau_B = 0.1\text{--}2.0$ Myr (long model). Second, the variability of $B_{\star}$ due to stellar magnetic cycles with $\tau_{\text{cyc}} = 10^1\text{--}10^4$ years (short model). The strength of these variations depends on the relation between the timescale of the changing magnetic field (τ_B

or τ_{cyc}), the spin-up timescale (τ_{spin}), and the viscous timescale of the accretion disk (τ_v).

In the case of $\tau_B \ll \tau_{\text{spin}} \sim 2\text{--}3$ Myr, the stellar spin is slow to adjust to the changing parameters, and ω_s is shifted out of its ZTS. If the variations occur on long timescales $\tau_B \sim \tau_{\text{spin}}$, the stellar spin can adjust to the change and remain closer to its ZTS. On shorter timescales, the effect of magnetic cycles on ω_s is weaker if they occur on shorter timescales than the viscous timescale of the inner disk $\tau_{\text{cyc}} \ll \tau_{v,\text{in}} \sim 10^3$ years. The inner disk material is slow to adjust to the changing parameters, resulting in a back-reaction in the accretion rate. For $\tau_{\text{cyc}} \gg \tau_{v,\text{in}}$, this back-reaction is less pronounced and the effect on ω_s increases. Our results can explain at least part of the observed low values ω_s . Another possibility that could explain the differences between expected and measured ω_s values is outflows and winds from the inner disk region. These winds can transport significant amounts of AM and affect the stellar spin state. In the next iteration of our star-disk model, we focus on these (time-dependent) disk winds in different configurations. We encourage further theoretical and observational work that connects accretion, stellar rotation, and magnetic properties in T Tauri stars.

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