SPIN OF ACCRETING STARS: ACCRETION POWERED STELLAR WINDS VS. DISK LOCKING. S. Matt, *Department of Astronomy, University of Virginia, Charlottesville VA 22903, USA*, R. E. Pudritz, *Department of Physics & Astronomy, McMaster University, Hamilton ON L8S 4M1, Canada.*

We find that a stellar wind can counteract the spin-up torque from mass accretion, solving the mystery of why accreting pre-main-sequence stars are observed to spin at less than 10% of break-up speed. This requires that the mass outflow rate in the stellar wind, $\dot{M}_w$, is $\sim 10\%$ of the accretion rate, $\dot{M}_a$. We suggest that such massive winds will be driven by some fraction ϵ of the accretion power. For observationally constrained typical parameters, ϵ needs to be of the order of 10%. In this scenario, efficient braking of the star will terminate simultaneously with accretion, as is usually assumed to explain the rotation velocities of stars in young clusters.

1. BACKGROUND

Classical T Tauri stars are surrounded by Keplerian disks and accrete substantial amounts of angular momentum along with infalling matter and energy. The typical accretion torque on these stars is sufficient to spin them up to break-up speed in less than 10^6 yrs (Hartmann & Stauffer, 1989). The fact that many CTTSs (the "slow rotators") spin at $\lesssim 10\%$ of break-up (Bouvier et al., 1993) and have ages longer than their spin-up times, suggests that they are in spin equilibrium, wherein they somehow rid themselves of accreted angular momentum and thereby maintain a net zero torque. Furthermore, in order to explain the distribution of rotational velocities of stars in young clusters, it is generally believed (Edwards et al., 1993; Bodenheimer, 1995, for a review) that rotational braking of the star becomes inefficient when accretion ceases.

The leading explanation for angular momentum loss during accretion, referred to as "disk locking" (Ghosh & Lamb, 1978; Königl, 1991; Shu et al., 1994), requires a significant spin-down torque on the star arising from a magnetic connection between the star and disk. However, Matt & Pudritz (2005b, and references therein) discussed some severe problems with the disk locking scenario, as follows: 1) After more than a decade, observational support for disk locking is still controversial (e.g., Stassun et al., 2001; Herbst et al., 2002). 2) T Tauri stars do not appear to have the strong dipole fields required for disk locking of the slow rotators (Safier, 1998; Johns-Krull et al., 1999). 3) The stellar magnetic field topology should be largely open (see Fig. 1), rather than connected to the disk, due to a stellar wind (Safier, 1998) and differential twisting between the star and disk (Uzdensky et al., 2002). The presence of open stellar field lines allows for, and may be caused by, a stellar wind, and the immediate question is whether a wind along these open lines carry away enough angular momentum to counteract the accretion torque (Hartmann & Stauffer, 1989; Tout & Pringle, 1992). Recent evidence for a stellar wind has also been discovered by Dupree et al. (2005)

2. THEORY

In order to explain the slow spin of accreting T Tauri stars, we propose to replace the disk-locking model with a scenario in which a fraction of the energy deposited by accretion onto the star powers a stellar wind. Here we outline the basic idea and refer the reader to Matt & Pudritz (2005a) for details. The **spin-up torque** on the star from the accretion of disk matter is (e.g., Matt & Pudritz, 2005b)

$$\tau_a = \dot{M}_a \sqrt{GM_* R_t}, \quad (1)$$

where G is the gravitational constant, M_* is the mass of the star, and R_t is the location of the inner edge of the disk, from which material falls onto the stellar surface (Königl, 1991). Basic stellar wind theory (e.g., Mestel, 1984) gives the **spin-down torque** on the star from its wind as

$$\tau_w = -\dot{M}_w \Omega_* R_*^2 (r_A/R_*)^2, \quad (2)$$

where we've neglected a factor of order unity, Ω_* is the angular spin rate of the star, R_* is the stellar radius, and r_A is the Alfvén radius, defined as the location where the wind velocity reaches the local Alfvén speed.

In spin-equilibrium (neglecting other torques), $\tau_a = -\tau_w$, which gives

$$f_{eq} \approx 0.1 \times \left(\frac{r_A/R_*}{15}\right)^{-2} \left(\frac{\dot{M}_w/\dot{M}_a}{0.1}\right)^{-1} \left(\frac{R_t/R_*}{2}\right)^{1/2} \quad (3)$$

where f_{eq} is the equilibrium spin rate of the star expressed as a fraction of break-up speed. **It is clear from equation 3 that a stellar wind alone can counteract the spin-up effects of accretion**, under two conditions: 1) the wind magnetic "lever

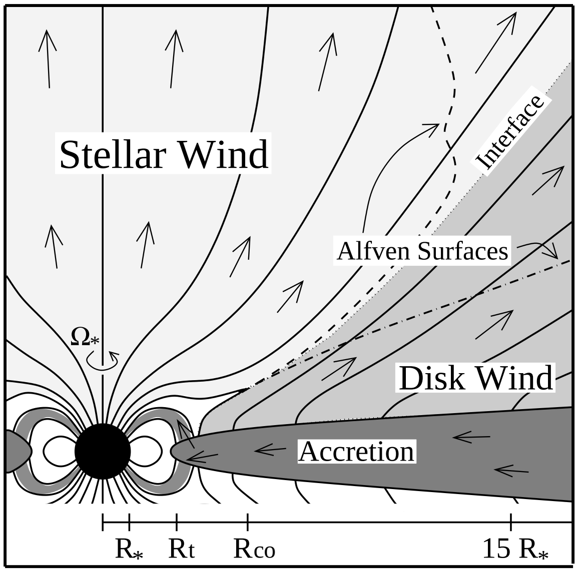

Figure 1: Schematic of the star-disc interaction. The inner edge of the disk is connected to the stellar magnetic field, which regulates the transfer of matter, energy, and angular momentum to the star. The stellar wind extracts angular momentum from the star. See §3.

arm," r_A, must be reasonably long, and 2) the mass loss rate of the wind should be a substantial fraction of the accretion rate. When $\dot{M}_w/\dot{M}_a \sim 0.1$, and using a dipole field strength an order of magnitude smaller than required by disk locking models, we estimate that the value of r_A/R_* for T Tauri stars should not be too different from the solar wind value of 12–16 (Li, 1999).

In order for the stellar wind mass loss rate to be a substantial fraction of the accretion rate, powerful wind driving is required. We propose that the thermal energy of the stellar wind is powered by accretion, which gives

$$\frac{\dot{M}_w}{\dot{M}_a} \approx 0.1 \left(\frac{\epsilon}{0.15}\right) \left(\frac{\Gamma_{th}}{1}\right)^{-1} \times \left(\frac{1 - 0.5 R_*/R_t - f_{eq}(R_t/R_*)^{1/2}}{0.6}\right), \quad (4)$$

where ϵ is the efficiency of the power coupling between accretion and the stellar wind, Γ_{th} is a wind parameter that relates the thermal energy to the gravitational energy, and the term on the second line of the equation tabulates the energy arriving near the stellar surface that is available to power the wind (see Matt & Pudritz, 2005a, for details). For the fiducial values in equation 4, we have used $f_{eq} = 0.1$, $R_t/R_* = 2$, and adopted a value of $\Gamma_{th} = 1$, which we derive from observations of T Tauri stars and which is of the same order as the solar wind value. Together, equations 3 and 4 indicate that, in order for an accretion powered stellar wind to counteract the spin-up torque from accretion, $\sim 10\%$ of the accretion energy deposited on the star must be transferred to the stellar corona, and ultimately into its wind.

2. COMPLETE PICTURE OF STAR-DISK INTERACTION

Figure 1 is a synthesis of the results of many studies in the literature of the star-disk interaction and best illustrates the proposed scenario. In the figure, the stellar dipole magnetic field connects only to a small portion of the disk inner edge. There, disk material is chanelled by the magnetic "funnel" to the polar region of the star, depositing mass, energy, and angular momentum. The star is rotating sufficiently slowly that the corotation radius, R_{co} is outside the connected region, so the star feels only a spin-up torque from its interaction with the disk. At the same time, there is a powerful wind along the open stellar field. The stellar wind Alfvén surface (dashed line) is near 15 R_* at mid latitudes, and crosses the poles at much larger radii, giving an effective lever arm length of approximately 15 R_*. A disk wind is also present, which extracts angular momentum from the disk. The Alfén surface of the disk wind (dash-dotted line) gives an effective lever arm that is a few times the radius of the footpoint of the field lines from which the wind flows. The disk and stellar winds collimate on a scale larger than the figure. Finally, the sheared interface between the two winds is likely to be interesting and produce observable signatures—namely shocks; Kelvin-Helmholz instabilities; and there exists a current sheet that should give rise to magnetic reconnections and particle acceleration.

We expect that there is a threshold value of $\dot{M}_a$, below which the contraction of the star is more important than accretion torques. At this later time, stellar spin evolution could be controlled by the interplay between contraction to the main sequence and a conventional stellar wind. Thus, an intrinsic spread in the timescale for the decline of accretion could explain the distribution of rotational velocities in young clusters (Edwards et al., 1993), in the same manner as usually attributed to disk locking.

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