The Astrophysical Journal, 632:L135–L138, 2005 October 20

ACCRETION-POWERED STELLAR WINDS AS A SOLUTION TO THE STELLAR ANGULAR MOMENTUM PROBLEM

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Received 2005 June 27; accepted 2005 September 14; published 2005 October 12

ABSTRACT

We compare the angular momentum extracted by a wind from a pre–main-sequence star to the torques arising from the interaction between the star and its Keplerian accretion disk. We find that the wind alone 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 breakup speed, provided that the mass outflow rate in the stellar winds is ~10% of the accretion rate. We suggest that such massive winds will be driven by some fraction ϵ of the accretion power. For observationally constrained typical parameters of classical T Tauri stars, ϵ needs to be between a few and a few tens of percent. 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.

Subject headings: accretion, accretion disks — MHD — stars: magnetic fields — stars: pre–main-sequence — stars: rotation — stars: winds, outflows

1. INTRODUCTION

Pre–main-sequence stars surrounded by Keplerian disks accrete substantial amounts of angular momentum along with infalling matter and energy. Classical T Tauri stars (CTTSs) are widely understood to be low-mass ($\lesssim 2\,M_\odot$) pre–main-sequence stars with ages ranging from a few times 10^5 to a few million years and represent the latest stages of protostellar accretion. The typical accretion torque on these stars is sufficient to spin them up to breakup speed in much less than 10^6 yr (Hartmann & Stauffer 1989). The fact that many CTTSs (the "slow rotators") spin at $\lesssim$10% of breakup (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 (2005 and references therein) discussed several severe problems with the disk locking scenario, most notably that the stellar magnetic field topology should be largely open, rather than connected to the disk. 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 carries away enough angular momentum to counteract the accretion torque (Hartmann & Stauffer 1989; Tout & Pringle 1992).

In this Letter we report (in § 2) that protostellar winds can remove accreted angular momentum, even for slow stellar rotation rates, provided that the stars have large mass-loss rates. We propose that the energy driving the stellar wind derives from accretion power (§ 3), and this also explains the apparent connection between efficient braking and accretion. In § 4 we combine the results of many studies of the star-disk interaction to give a complete picture for the flow of matter and angular momentum near the star.

2. SPIN EQUILIBRIUM

We consider long-term torques, averaged over ~10^4 yr (i.e., much less than spin-up/down times). The approximation of a steady state and the adoption of global, axisymmetric magnetic fields are thus acceptable, even though the magnetic structure, winds, and accretion properties are variable and probably not axisymmetric, on much shorter timescales. The torque on the star, due to the accretion of disk matter, is

$$\tau_a = \dot{M}_a \sqrt{G M_* R_t} \tag{1}$$

(e.g., Matt & Pudritz 2005),[4] where $\dot{M}_a$ is the mass accretion rate, 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 essentially free-falls onto the stellar surface (Königl 1991). In the following, we compare this accretion torque with the torque originating from a stellar wind.

X-ray observations (Feigelson & Montmerle 1999) and magnetic field measurements (Johns-Krull et al. 1999; Smirnov et al. 2003) of CTTSs reveal the presence of hot coronae and dynamically important fields. Together with the rotation rates, these observations suggest that CTTSs drive stellar winds by coronal thermal pressure (similar to the Sun) and that magnetocentrifugal effects may also play a role. Furthermore, Dupree et al. (2005) recently reported evidence for hot (~3×10^5 K), fast (~400 km s^{-1}) stellar winds from two CTTSs. Thus, we believe it is appropriate to adopt standard magnetohydrodynamic (MHD) wind theory (e.g., Weber & Davis 1967; Mestel 1968, 1984; Sakurai 1985; Kawaler 1988) for

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[4] We have neglected a term proportional to the spin rate of the star, but eq. (1) is valid for spin rates well below breakup speed.

these systems. In this case, the torque on the star, due to angular momentum lost to the wind, is given by

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

(e.g., Mestel 1984),[5] where $\dot{M}_w$ is the mass-loss rate in the stellar wind, 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. The dimensionless factor of order unity κ takes into account the geometry of the wind ($\kappa = \frac{2}{3}$, for a spherically symmetric wind). In essence, wind theory tells us that magnetized stars spin "with their arms out," and the resulting spin-down torque depends most strongly on the length of their lever arm, r_A.

Assuming that a spin-down torque arising from a disk connection and spin-up due to contraction are negligible, the equilibrium spin rate of the star is determined by the balance of accreted angular momentum with the spin-down torque from the stellar wind (Hartmann & Stauffer 1989). By equating $\tau_a = -\tau_w$ (eqs. [1] and [2]), the equilibrium stellar spin rate is

$$f_{\rm eq} \approx 0.09 \left(\frac{\kappa}{2/3}\right)^{-1} \left(\frac{R_t/R_*}{2}\right)^{1/2} \left(\frac{r_A/R_*}{15}\right)^{-2} \left(\frac{\dot{M}_w/\dot{M}_a}{0.1}\right)^{-1}, \quad (3)$$

where we have expressed the spin rate as a fraction of the breakup speed, $f \equiv \Omega_* R_*^{3/2} (GM_*)^{-1/2}$. It is immediately evident that stellar winds alone are capable of keeping CTTSs spinning well below the breakup rate, provided that they drive powerful (i.e., large $\dot{M}_w$) winds and have a long magnetic lever arm.

This result depends most strongly on the length of the lever arm, which is an uncertain parameter. The usual analytic calculation of r_A/R_* (e.g., Kawaler 1988; Tout & Pringle 1992) is not very reliable, as it employs a one-dimensional formulation (instead of the two-dimensional problem here), and it depends strongly on the assumed magnetic geometry and wind speeds. However, the analytical result is still useful because it tells us r_A/R_* depends on the ratio $B_*^2 R_*^2/\dot{M}_w$ (where B_* is the field strength at the stellar surface) for a given magnetic geometry and wind speeds. Using the well-studied example of the solar wind, we can get an initial estimate of r_A, as follows. First we assume that CTTS wind speeds are within a factor of a few of solar wind values, which we expect from the similar escape speeds and is supported by observations. Second, for a lack of information to the contrary, we assume that the magnetic geometry in CTTS winds is also not too different from solar. Now, using the observational limit on the large-scale (dipole) component of CTTS magnetic fields of $B_* \sim 200$ G (Johns-Krull et al. 1999; Smirnov et al. 2003), and assuming $R_* = 2\ R_\odot$, the ratio $B_*^2 R_*^2/\dot{M}_w$ is equal to the solar wind value when $\dot{M}_w \sim 2 \times 10^{-9}\ M_\odot\ {\rm yr}^{-1}$. Remarkably, this is approximately 10% of typical observed accretion rates (Johns-Krull & Gafford 2002). Thus, for this value of $\dot{M}_w$, the lever arm length should be close to the solar value of 12–16 (Li 1999) and larger if $\dot{M}_w$ is smaller. Furthermore, this value of r_A is consistent with numerical simulation results (e.g., Matt & Balick 2004), when scaled for CTTS winds, even for rotation rates of 10% of breakup. Therefore, we believe that $r_A/R_* \gtrsim 15$ is reasonable, and the fiducial value in equation (3) is justified.

The relationship $\dot{M}_w \sim 0.1\dot{M}_a$ is consistent with the stellar outflow rates reported by Dupree et al. (2005), as well as the large-scale mass outflow rates inferred in these and younger systems (Königl & Pudritz 2000). As further support, a coronal wind with $\dot{M}_w \lesssim 10^{-9}\ M_\odot\ {\rm yr}^{-1}$ is consistent with CTTS X-ray luminosities (Decampli 1981). In the following section, we show that accretion power is capable of driving massive stellar winds such as these.

3. ACCRETION POWER

If the stellar wind alone counteracts the accretion torque, equation (3) indicates that $\dot{M}_w$ should be a substantial fraction of $\dot{M}_a$, which requires powerful wind driving. The observations discussed in § 2 indicate that CTTSs have enhanced rotational, thermal, and magnetic energies in their coronae, relative to the present-day Sun, suggesting that CTTS winds will be substantially more energetic and massive than the solar wind. It is not yet clear, however, whether scaled-up solar-type activity alone can drive high enough mass loss to satisfy equation (3) (Decampli 1981; Tout & Pringle 1992; Kastner et al. 2002). Instead, we propose that the stellar wind is powered by the energy deposited on the star via accretion. This scenario is supported by observations of hot stellar outflows (Beristain et al. 2001; Edwards et al. 2003; Ferro-Fontán & Gómez de Castro 2003; Dupree et al. 2005).

The details of the complicated interaction between the star and disk are not important for tabulating the accretion power. Instead, this can be characterized as an inelastic process, wherein rotating disk material attaches itself to the stellar magnetosphere at R_t and eventually falls onto and becomes part of the star. What matters is the difference in the energy before and after this interaction. In particular, disk matter that falls from R_t to R_* liberates gravitational potential energy and also transfers its orbital kinetic energy onto the star. Some of this energy is added to the rotational kinetic energy of the star (at a rate $\Omega_* \tau_a$), and, in spin equilibrium, is balanced by the work done by the stellar rotation on the wind (at a rate $\Omega_* \tau_w$). The remaining accretion power is[6]

$$L_a = 0.5\dot{M}_a v_{\rm esc}^2 [1 - 0.5R_*/R_t - f(R_t/R_*)^{1/2}], \quad (4)$$

where $v_{\rm esc}$ is the escape speed from the stellar surface. The terms in the square brackets represent the sum of the change in potential energy ($1 - R_*/R_t$) and the change in kinetic energy ($0.5R_*/R_t$) of accreting material, minus the work done on the stellar rotation [$f(R_t/R_*)^{1/2}$]. It is L_a that is deposited near stellar surface by accretion, and thus L_a powers energetic accretion phenomena, such as excess luminosity (Königl 1991) and a stellar wind.

We suggest that there are a number of possible ways in which some of this energy will transfer to the open field region of the stellar corona. Accretion shocks (Königl 1991; Kastner et al. 2002), and possibly magnetic reconnection events (Hayashi et al. 1996), give rise to X-rays and UV excesses, which radiate the stellar surface. Shock-heated gas may diffuse or mix across closed field regions and into the stellar wind region, and thermal conduction may be significant. Time-dependent accretion events will excite magnetosonic waves that may propagate

[5] Eq. (2) is valid for any magnetic geometry. Kawaler (1988) used a different formulation for a dipolar magnetic field, but this was a misinterpretation of eq. (12) in Mestel (1984), which requires stellar surface values of density and velocity, instead of the total mass outflow rate $\dot{M}_w$.

[6] We have neglected terms proportional to f^2, which are important only for fast rotation.

throughout the corona and deposit energy through wave dissipation. In general, these processes increase the thermal energy in the corona, and the details are not necessary for the estimate that follows.

An MHD wind can be powered by both the rotational kinetic energy of the star and by coronal thermal energy (Washimi & Shibata 1993). We propose that the thermal component is powered by some fraction ϵ of the accretion power L_a. The thermal power in the wind is approximately $\dot{M}_w v_s^2(\gamma - 1)^{-1}$, where v_s is the sound speed near the stellar surface and γ is the polytropic index (i.e., $P \propto \rho^\gamma$). Setting this equal to ϵL_a gives

$$\dot{M}_w/\dot{M}_a = \epsilon\Gamma_{\rm th}^{-1}\left[1 - 0.5R_*/R_t - f(R_t/R_*)^{1/2}\right], \qquad (5)$$

where $\Gamma_{\rm th} \equiv 2(v_s/v_{\rm esc})^2(\gamma - 1)^{-1}$ relates the thermal energy to the gravitational potential energy. In reality, the parameter $\Gamma_{\rm th}$ is not independent of ϵ, since the mechanism(s) by which accretion energy powers the wind influences the gas temperature (and thus v_s), and the location and rate of energy deposition influences the effective γ.

This formulation of the problem is advantageous, as it is valid for wind temperatures ranging from hot, in which thermal pressure dominates the wind dynamics, to cold, in which magnetocentrifugal effects dominate (i.e., fast magnetic rotator winds). The energy equation (5) can be combined with the torque equation (3) to solve for $f_{\rm eq}$ and $\dot{M}_w/\dot{M}_a$, simultaneously, for any given coupling efficiency ϵ and thermal energy parameter $\Gamma_{\rm th}$. Assuming $\gamma = 5/3$, the observed X-ray temperatures and the observations of Dupree et al. (2005) suggest that the value of $\Gamma_{\rm th}$ for CTTSs is likely to be in the range 0.3–3. Adopting the fiducial values of equation (3), this likely range of $\Gamma_{\rm th}$ requires a power coupling efficiency in the range $4\% \lesssim \epsilon \lesssim 40\%$ to achieve the ratio of stellar mass-loss rate to disk accretion rate of $\dot{M}_w/\dot{M}_a \approx 0.1$ and an equilibrium spin $f_{\rm eq} \approx 0.09$. This value of ϵ appears reasonable and should help to discriminate between different possible energy transfer mechanisms.

4. SYNTHESIS

Figure 1 illustrates our proposed scenario for the dynamics and angular momentum evolution of the combined star-disk system. This is a synthesis of many results from the literature on disk winds (e.g., Ouyed & Pudritz 1997), stellar winds (e.g., Matt & Balick 2004), funnel flow accretion (e.g., Romanova et al. 2002), and the general star-disk interaction. In the figure, the stellar dipole magnetic field connects only to a small portion of the disk inner edge, as in "state 1" of Matt & Pudritz (2005). From there, disk material is channeled 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, $R_{\rm co} \equiv f^{-2/3}R_*$, is outside the connected region, and 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 midlatitudes and crosses the pole at a much larger spherical radius, giving an effective cylindrical lever arm length $r_{\rm A}$ of approximately $15R_*$.

With an estimate of $r_{\rm A}$, it is possible to consider the influence of rotation on the wind, since magnetocentrifugal effects begin to be important when $r_{\rm A}$ is greater than $R_{\rm co}$. Sakurai (1985) showed (see his Fig. 2) that for $v_s/v_{\rm esc}$ equal to the solar wind value, centrifugal acceleration is of equal importance with thermal driving when $r_{\rm A}/R_{\rm co} \sim 100^{1/3}$. For a star rotating at 10% of breakup, this means that equality of thermal and centrifugal effects occurs when $r_{\rm A}/R_* \sim 22$. The logical conclusion is that centrifugal effects will be at least marginally important in CTTS winds when $\dot{M}_w \gtrsim 10^{-9}\ M_\odot\ {\rm yr}^{-1}$ and may dominate for much lower values of $\dot{M}_w$ (since $r_{\rm A}$ is then larger) or faster rotation rates. Even with marginal centrifugal effects, these winds should be self-collimated, and most wind parameters (e.g., $r_{\rm A}$) depend on Ω_* (Washimi & Shibata 1993; Matt & Balick 2004). Furthermore, at large distances from any magnetic rotator, wind material possesses angular momentum equivalent to an amount as if the wind were corotating at $r_{\rm A}$ (e.g., Michel 1969). Thus, CTTS winds should rotate at a speed comparable to that of a disk wind (Bacciotti et al. 2002; Anderson et al. 2003) at observationally resolved distances from the star.

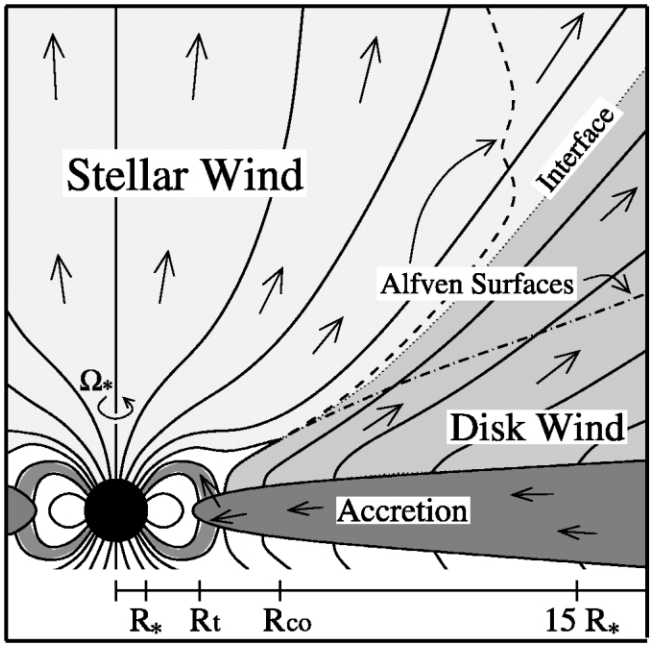

FIG. 1.—Schematic of the star-disk interaction. The inner edge of the accretion disk, located at R_t, is connected to the stellar magnetic field (*solid lines*), which regulates the transfer of matter, energy, and angular momentum to the star (*filled circle*). Arrows indicate the direction of both matter and angular momentum flow. The dashed and dash-dotted lines indicate the location of the Alfvén surfaces in the stellar and disk winds, respectively.

As shown in Figure 1, a disk wind is present that extracts angular momentum from the disk. The Alfvén surface of the disk wind (*dot-dashed 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. It is evident that the presence of the accretion disk is likely to affect the stellar wind. In particular, the disk wind can help to collimate the stellar wind (e.g., Pelletier & Pudritz 1992; Ouyed & Pudritz 1997), acting as a hydrodynamic "channel." This would result in shallower magnetic and thermal pressure gradients and possibly increase $r_{\rm A}$, relative to the case of an isolated stellar wind. Finally, the sheared interface between the two winds is likely to produce observable signatures from interesting phenomena, such as shocks and Kelvin-Helmholz instabilities, and there exists a current sheet that should give rise to magnetic reconnections and particle acceleration.

In essence, the accretion-powered stellar wind model solves the stellar angular momentum problem in the same way that a disk wind aids angular momentum transport in the disk (see

Königl & Pudritz 2000 for a review). Both the star and disk may drive accretion-powered magnetic outflows that are ~10% of $\dot{M}_a$. In the case of the disk, the local rotation rate is at breakup, so a short lever arm is sufficient to provide angular momentum transport there. The star, on the other hand, has a much stronger magnetic field than the disk, resulting in a longer lever arm, and so an equilibrium spin rate of much less than breakup speed is possible.

The configuration of Figure 1, as well as the possibility that the most significant spin-down torques on the star originate from open stellar field lines, is well supported by the numerical MHD simulations of Goodson & Winglee (1999) and (von Rekowski & Brandenburg (2004, 2005; but see Romanova et al. 2002). This picture may also apply to accreting systems other than CTTSs, such as cataclysmic variables, binary X-ray pulsars, and accreting black holes.

5. CONCLUSION

We propose that the slow spin of CTTSs is explained by a balance between the spin-up torque from accretion and the spin-down torque from a stellar wind (eq. [3]). In this scenario, some fraction (ϵ) of the energy released by accretion ultimately powers a stellar wind with a large mass-loss rate ($\dot{M}_w \sim 0.1\dot{M}_a$) and rapid angular momentum loss. Furthermore, 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 time-scale for the decline of accretion could explain the distribution of rotational velocities in young clusters (Edwards et al. 1993), in the same manner as that usually attributed to disk locking.

Our analysis is free from the problems facing disk-locking models discussed by Matt & Pudritz (2005). In particular, the X-wind (Shu et al. 1994 and subsequent work) and standard star-disk torque models (Ghosh & Lamb 1978; Königl 1991) require a large-scale magnetic field that is stronger than current observations allow. These models also assume an unrealistically strong magnetic connection between star and disk and neglect any torque contribution from a stellar wind. In this Letter we showed that a stellar wind is capable of providing significant torques, even when the magnetic field is an order of magnitude weaker than that required by disk-locking models. Our estimate of r_A (§ 2) suggests that CTTSs have sufficiently long lever arms, but this calculation should be made more precise.

Observations of the hot, possibly stellar outflows can further constrain our model. More high-resolution spectroscopy (e.g., Kastner et al. 2002; Dupree et al. 2005) may reveal stellar wind signatures that will provide better constraints on $\dot{M}_w$, Γ_{th}, and ϵ. Finally, additional measurements or limits on the large-scale magnetic field (e.g., Johns-Krull et al. 1999; Smirnov et al. 2003) would be useful to constrain the value of r_A.

We are grateful for discussions with Robi Banerjee and Alison Sills, useful remarks from the anonymous referee, funding from McMaster University, and a grant from NSERC of Canada.

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