RevMexAA (Serie de Conferencias), **1**, 309-316 (1995)

OBSERVATIONAL EVIDENCE FOR THE IMPORTANCE OF MAGNETOSPHERES IN THE EVOLUTION OF T TAURI ACCRETION DISK SYSTEMS

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RESUMEN

Las magnetosferas deben de jugar un papel activo en la evolución del momento angular de objetos estelares jóvenes de masa pequeña durante la fase de acrecimiento de disco. El acoplamiento entre la magnetosfera estelar y la parte interior del disco de acrecimiento en sistemas T Tauri clásicos provee de forma natural la regulación aparente de la velocidad angular de la estrella central en presencia del disco de acrecimiento, desafiando de esta forma su tendencia a incrementar la rotación, debido ésto tanto al acrecimiento con material del disco con gran momento angular, como a la propia contracción que le conduce a la secuencia principal.

Diversas observaciones sugieren que las estrellas T Tauri tienen dos zonas de flujos, una con un chorro colimado moviéndose a gran velocidad, y otra con un flujo con velocidad mucho menor. Si esto es así, entonces es posible que las magnetosferas, tanto del disco como de la estrella, estén implicadas en la conducción de los vientos.

ABSTRACT

Magnetospheres must be integral components in the angular momentum evolution of low mass young stellar objects during the phase of disk accretion. Coupling between the stellar magnetosphere and the inner accretion disk in classical T Tauri systems accounts naturally for the apparent regulation of the angular velocity of the central star in the presence of disk accretion, in defiance of its tendency to spin-up both from accretion of disk material of high specific angular momentum and from contraction toward the main-sequence. Observational support for the magnetosphere-disk interaction includes (1) kinematic evidence for mass infall at free fall velocities onto the star and (2) photometric evidence for rotational modulation from hot spots on the stellar surface.

The angular momentum which is apparently extracted from the accreting star is likely carried away by a magnetized wind, but whether the magnetosphere of the star or the disk is the primary agent channeling the outflow is not yet known. Recent observations of forbidden line emission from T Tauri stars suggests that there may be two separate outflow zones. One is a high velocity collimated jet, with ratios of mass loss rate in the outflow to mass accretion rate in the disk $\sim 10^{-2}$, and is found only among the T Tauri stars with large near infrared excesses. The second one, characterized by a much lower outflow velocity and uncertain mass loss rates, is found in all T Tauri stars with signatures for disk accretion. If classical T Tauri stars do have two separate outflow mechanisms, possibly both stellar and disk magnetospheres may be implicated as agents in driving winds from accretion disk systems.

Key words: **STARS: ROTATION — STARS: MASS LOSS — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

Standard accretion disk models successfully account for basic features of the spectral energy distributions of classical T Tauri stars, with infrared excesses attributed in part to viscous energy dissipation in a self-luminous accretion disk and optical continuum "veiling" excesses attributed to energy released in a "boundary layer" interface between the star and the inner Keplerian disk. The disk accretion rates are most reliably estimated from the luminosity of the optical continuum excess emission, with typical values of $\dot{M}_{acc} \sim 10^{-7}$ $M_\odot$ yr^{-1}. However, standard models fail to account for two fundamental observational phenomena of classical T Tauri stars:

(1) *Angular velocities of T Tauri stars are considerably lower than break-up.* A star accreting material from the inner Keplerian disk at the inferred accretion rates will be spun to order break-up over the observed disk lifetimes (Hartmann & Stauffer, 1989). However, despite the expectation that accretion will affect the stellar angular momentum profoundly, observed *vsini* distributions for T Tauri stars reveal that most have projected equatorial velocities < 20 km s^{-1}, corresponding to angular velocities $\Omega_* \sim 0.1 \ \Omega_{break-up}$ (Bouvier 1990; Vogel & Kuhi 1981). This suggests that angular momentum is efficiently extracted from the star during the phase of disk accretion.

(2) *T Tauri winds are found only among those stars with accretion disks.* Sensitive measurements of accretion and wind diagnostics reveal that energetic T Tauri winds are found *only* in classical T Tauri stars with near infrared and optical continuum excesses arising from disk accretion. Further, the correlations between wind and accretion diagnostics strongly suggest that the winds are powered by a source related to disk accretion (Hartigan, Edwards, Ghandour 1995; Edwards, Ray, & Mundt 1993; Cabrit et al. 1990). These energetic winds are excellent candidates to carry angular momentum out of the star/disk system.

Taken together, these observations suggest that accretion disk systems must provide a mechanism to extract angular momentum from the central forming star and carry it out of the system via energetic accretion driven winds. In this article, we briefly summarize salient observational properties suggesting that stellar and/or disk magnetospheres are necessary agents in this angular momentum transfer.

2. REGULATION OF THE STELLAR ANGULAR VELOCITY

Recent comparisons of photometrically determined rotation periods of low mass pre-main sequence stars of comparable mass and age between objects with (classical T Tauri stars, cTTS) or without (weak T Tauri stars, wTTS) accretion disk signatures reveal that cTTS have rotation periods averaging a factor of 2 to 4 times slower than their wTTS counterparts (Edwards et al. 1993; Bouvier et al. 1993, 1995). Moreover, the cTTS rotation periods inferred from photometric modulation are confined to a fairly narrow range, on the order of 8 days. These observations suggest that T Tauri stars in accretion disk systems are subjected to a regulation of their angular velocities, countering the tendency to spin up both from accretion of disk material of high specific angular momentum and from readjustments in moment of inertia as they contract toward the main sequence.

Two basic mechanisms could in principle account for the spin down of accreting T Tauri stars, both of which rely on the existence of a strong *stellar* magnetosphere. Compelling evidence that T Tauri stars possess the requisite dynamo generated magnetospheres include observations of enhanced Zeeman sensitive lines (Basri, Marci, & Valenti 1992), x-ray flux levels about 1000× solar (Montmerle et al. 1993), and non-thermal cm-wave radio emission, which is sometimes spatially resolved into loops of several stellar radii (Phillips et al. 1995; André et al. 1992). The two options for stellar magnetospheres to extract angular momentum from the accreting star differ as to whether a closed or open field line geometry dominates the interaction with surrounding material:

(1) *Open Stellar Field Lines.* In this scenario, the accretion disk would meet the star in its equatorial plane, generating a classical shear boundary layer, and depositing angular momentum into the star. Open field lines at high latitude would then provide a path for a dynamo-driven wind to carry angular momentum from the star. This mechanism has been explored by Tout & Pringle (1992), who find that a balance between gain and loss of angular momentum leads to an estimate of a stellar rotation rate considerably below break-up. However, this approach does not suggest any natural explanation to *regulate* the angular velocity of the convective, accreting star, nor is the means for the dynamo to drive the wind identified.

(2) *Closed Stellar Field Lines.* In this scenario, closed field lines from the stellar magnetosphere would truncate the accretion disk at a radial distance of a few stellar radii, established by the balance between accretion and magnetic pressures. The MHD calculations exploring the coupling between the disk and the magnetosphere and the subsequent extraction of angular momentum from the star differ significantly (Ghosh & Lamb 1979; Königl 1991; Shu et al. 1994; Cameron & Campbell 1993; Ghosh 1995; Clark et al. 1995), but

all agree on a few fundamental points. In particular, magnetosphere/disk coupling models predict that (1) the central star will be regulated at an angular velocity equivalent to the Keplerian velocity at the disk truncation radius and (2) accretion of material onto the stellar surface will occur by mass loading field lines coupled to the disk, with material free-falling to the stellar surface along trajectories established by the field geometry.

Relying on a dynamo-driven stellar wind to spin down the star at first appears promising in light of the ubiquity of energetic winds in all accreting cTTs. However, the absence of T Tauri winds in the wTTS, even though these non-accreting stars rotate more rapidly and have more energetic dynamos than cTTS (Neuhauser et al. 1995), shows that *stellar winds* cannot be invoked to solve this problem. Moreover, additional observational evidence strongly favors the magnetosphere/disk coupling scenario. Not only does this mechanism predict a regulation of the stellar rotation period comparable to those observed, but it also offers an explanation for:

- *Kinematic evidence for mass infall at free-fall velocities:* Spectral line profiles indicative of mass infall at velocities up to several hundred km s^{-1} in upper Balmer and permitted metallic lines are found in most if not all cTTS spectra (Edwards et al. 1994; Appenzeller & Mundt 1989; Bertout 1989). The observed infall velocities and profile morphologies are in good agreement with radiative transfer calculations for optically thick lines formed in magnetospheric infall zones (Hartmann et al. 1994).
- *Photometric evidence for rotational modulation from hot spots:* Multiwavelength photometric monitoring of TTS reveals that while rotational modulation in wTTS derives from large cool starspots, light variations in many cTTS arise in spots hundreds to thousands of degrees hotter than the photospheres (Bouvier et al. 1995). Magnetospheric accretion in a dipole field tilted relative to the stellar rotation axis provides an explanation for this phenomenon, if reprocessing of the energetic photons from the accretion shock gives rise to the hot veiling continuum (Bertout 1989).

However, temporal variations in both of these observed properties suggest that non-uniform time-variable magnetospheric structures likely prevail, greatly complicating the observed phenomena. For example, variations in photometric periods are found among cTTS with hot spots (Simon et al. 1990; Bouvier et al. 1995) and

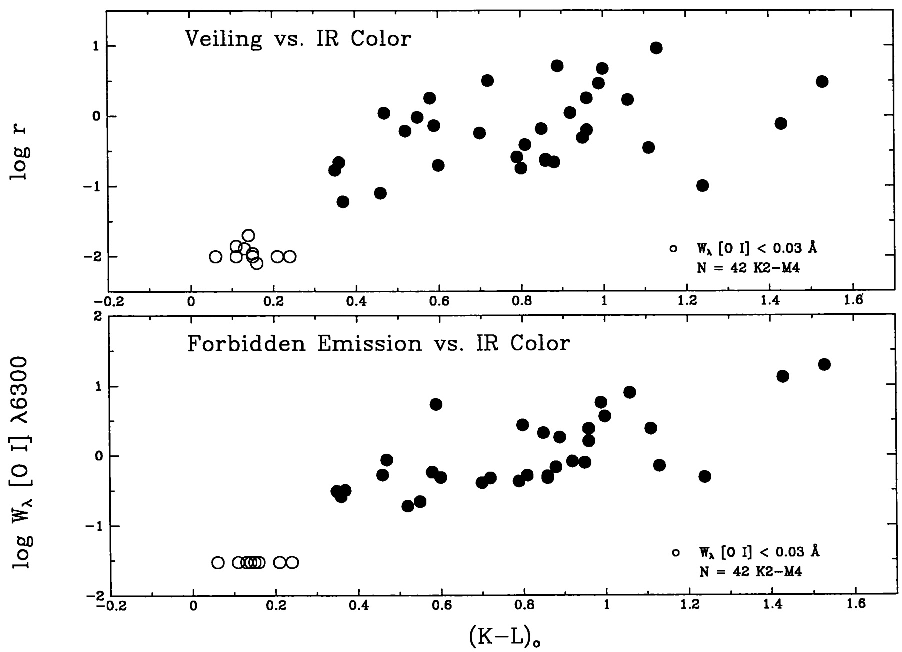

Fig. 1.— Plots of the optical continuum emission ("veiling", expressed as r, the ratio of veiling to photospheric flux at λ5500 Å) and equivalent width of the strongest forbidden emission line, [OI] λ6300, against the reddening corrected $(K-L)_o$ color index for 42 K and M TTS, from data presented in HEG. The cTTS all have veiling continuum attributed to boundary layer emission, forbidden line emission from winds, and near infrared color excesses from optically thick inner disk regions.

short term variations in line profiles formed in infalling material are observed (Edwards et al. 1994; Guenther & Hessman 1993). Ambitious spectroscopic and photometric monitoring programs will be required to provide a complete understanding of magnetosphere/disk coupling and the infall of disk material onto the stellar surface.

3. COLLIMATED ENERGETIC OUTFLOWS

The angular momentum extracted from the star in a magnetosphere/disk coupling scenario must be passed back into the disk. The T Tauri winds, diagnosed by broad forbidden lines and blueshifted absorption reversals in Hα and Na D lines, are an excellent candidate to carry this angular momentum from the accretion disk system. Our knowledge of T Tauri winds, despite many decades of observational and theoretical effort, does not provide definitive evidence for the mechanism removing angular momentum from the system. Recent observational programs to study T Tauri winds focus on forbidden lines as probes of wind morphology and mass loss rates (Hartigan, Edwards, & Ghandour 1995 [HEG]; Hirth, Mundt, & Solf 1994 [HMS]; Hamann 1994). Key results from recent forbidden line studies of T Tauri winds are summarized here:

(1) Sensitive spectroscopic measurements of forbidden lines and optical continuum veiling fluxes in T Tauri stars reveal that forbidden [O I] λ6300 emission is present in all cTTS, which have near infrared and optical continuum excesses arising from disk accretion, and is absent in all wTTS, which have photospheric near infrared colors and lack optical veiling excesses. This is shown for a sample of 42 K and M T Tauri stars in Figure 1.

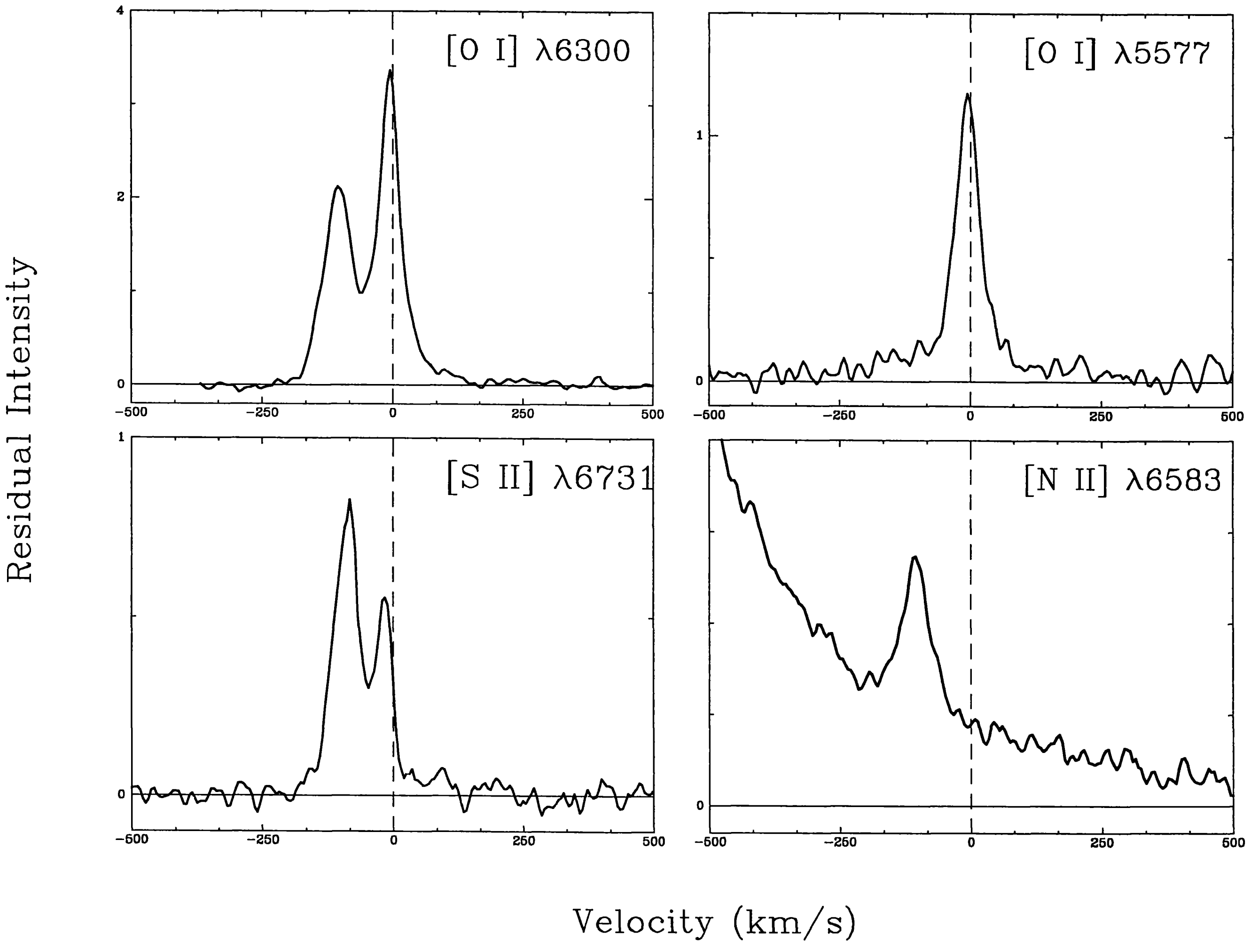

Fig. 2.— Residual forbidden line profiles in the cTTS CW Tau for four lines covering a range of critical densities from 10^4 to 10^8 cm^{-3}. Only the HVC is seen in [N II] and only the LVC is seen in [O I] λ5577.

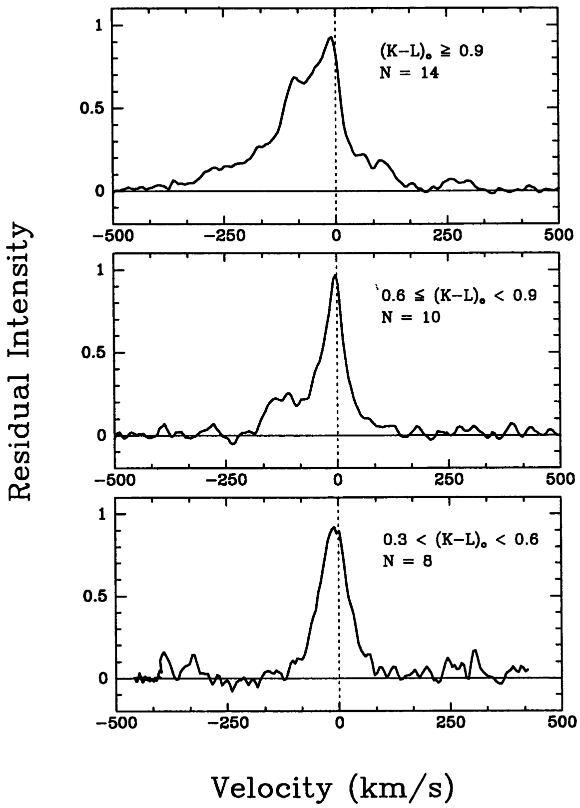

Fig. 3.— Each of the three panels represents an *average* [O I] $\lambda6300$ profile for the indicated number of cTTS in one of three $(K-L)_o$ intervals. A prominent blue wing and a strong HVC, identified as a jet, is typical of the systems with the largest near infrared color excesses. In the lower two panels, successively smaller values of $(K-L)_o$ are accompanied by successively less prominent contributions to the HVC.

(2) The broad, typically blueshifted, forbidden lines originate in two distinct regimes characterized by differing velocities, spatial extents, and physical conditions. The kinematic distinction and differing forbidden line ratios for the high velocity component (HVC) and the low velocity component (LVC) are shown for a representative cTTS in Figure 2.

(3) The HVC is formed in a *collimated jet*, with velocities $\sim$ 100 km s^{-1}, and spatial extents up to several arcsec (HMS), and its visibility correlates with the magnitude of the near infrared color excess (Figure 3; HEG). Mass loss rates can be estimated from the HVC of [O I] $\lambda6300$ assuming the lines are formed in shocked material in stellar jets. Shock modeling then provides temperature and density estimates from line ratios and jet mass loss rates are found to correlate with disk accretion rates derived from the veiling continuum luminosity. Typical ratios of $\dot{M}_{jet}/\dot{M}_{acc} \sim 10^{-2}$ are found for the shocked material radiating in the jets (HEG), as shown in Figure 5.

(4) The LVC is formed in a region that is denser, cooler, and less spatially extended than the HVC (HEG, HMS, Hamann 1994), but its centroid velocity is always shifted from the stellar velocity and it is spatially extended in some cTTS (Hirth, PhD thesis), *indicating the LVC is a second source of mass outflow.* Additionally, the LVC exhibits a velocity gradient, from smallest outflow velocities (5 to 10 km s^{-1}) for lines of highest critical density ([O I] $\lambda5577$) to largest outflow velocities (15 to 30 km s^{-1}) for lines of lowest critical density ([S II] $\lambda6731$), as illustrated in Figure 4. Mass loss rates for the LVC cannot be estimated until the heating mechanism is identified. However, the LVC is present in all cTTS with disk accretion diagnostics and the luminosity of the LVC correlates moderately well with the disk accretion rate, as shown in Figure 5.

In sum, recent forbidden line studies suggest that two physically distinct outflows are associated with TTS undergoing disk accretion. At the present time, identifying their origins is highly uncertain. However, the following points can be noted: (1) Collimated jets are only observed in those systems with the largest near

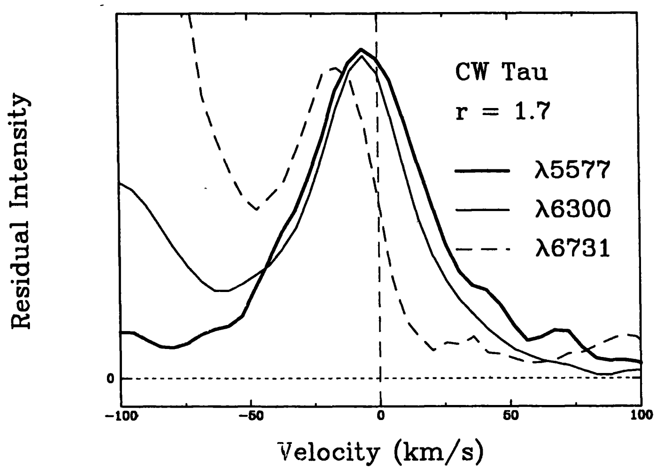

Fig. 4.— Normalized residual line profiles for 3 forbidden line profiles in the spectrum of the cTTS CW Tau. The line with the highest critical density, [O I] λ5577, has a centroid velocity blueshifted by 5 km s^{-1} relative to the stellar velocity, while the line with the lowest critical density is blueshifted by −16 km s^{-1}.

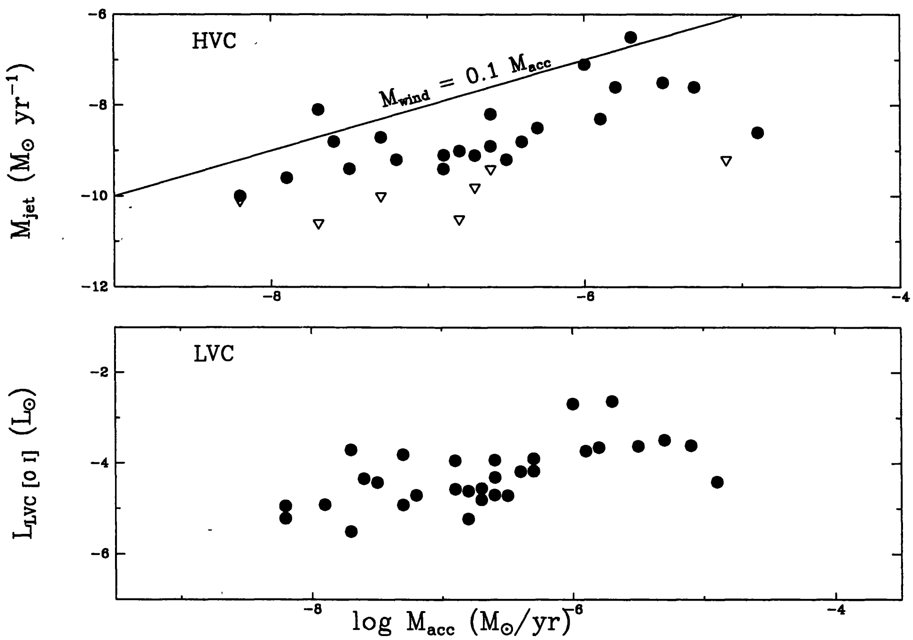

Fig. 5.— The upper panel shows the mass loss rate estimated from the HVC of [O I] λ6300, identified with a collimated jet, plotted against the disk accretion rate estimated from optical continuum veiling fluxes (HEG) for 32 cTTS. The open arrows are upper limits, for cTTS with low near infrared excesses and no detectable HVC emission. The lower panel is the luminosity of the LVC of [O I] λ6300 plotted against the disk accretion rate. Although the LVC is seen in all the cTTS, the heating mechanism is not known and mass loss rates cannot be identified for this slow outflow.

infrared color excesses, which have recently been interpreted as arising in infalling dusty envelopes (Calvet et al. 1994). The magnitude of the velocities in the jets, which are also similar to those in the blueshifted absorption features often seen at Hα (Edwards et al. 1987), suggest that they arise from a deep potential well, close to the stellar surface or inner disk regions, although their collimation mechanism is not yet identified. (2) The LVC, with slow but definite outflow velocities, a velocity gradient suggesting acceleration from regions of high to low density, and spatial extensions up to ∼ 100 AU, may be tracing the wind originating over the surface of the disk (HMS, HEG). (3) The fact that both outflows traced via forbidden lines are found only in TTS with disk accretion, and that the mass outflow rates or line luminosities correlate with disk accretion rates, suggest that the basic energy sources for both the HVC and LVC derive from gravitational potential energy released in the accretion process.

Until more is known about the origin and energetics of these accretion-driven outflows, firm statements about wind driving mechanisms and angular momentum loss cannot be made. However, most theoretical investigations suggest that outflows of magneto-centrifugal origin, with open magnetic field lines implanted in a rotating medium, are the most efficient means of powering accretion-driven outflows. Two general classes of models exist, distinguished by whether the rotating magnetosphere originates in the disk (Pudritz & Norman 1986; Königl 1989; Pelletier & Pudritz 1992; Safier 1993) or the star (Hartmann & MacGregor 1982; Shu et al. 1988; Shu et al. 1994).

The model for rotating stellar magnetospheres applied to slowly rotating T Tauri stars developed by Shu and collaborators synthesizes the key physical ingredients of both magnetocentrifugal disk-wind models and stellar magnetosphere -disk coupling models (Najita & Shu 1994; Ostriker & Shu 1995). The T Tauri magnetosphere truncates the inner disk, coupling to the disk only in a narrow region around the co-rotation radius. Just outside co-rotation, where the stellar field lines are forced to bow outward, material is lifted off the disk and forces the stellar field lines to open, resulting in a magnetocentrifugally driven wind. In this configuration, both the wind and accretion flow onto the star, with mass fluxes proportional to the disk accretion rate, would originate near the disk co-rotation radius.

Resolving which of these outflow/angular momentum loss scenarios applies in T Tauri accretion disk systems will require definitive observations identifying the point of origin of T Tauri winds. A promising observational approach is the synoptic spectroscopic study being undertaken by Johns & Basri (1995). They find that the TTS SU Aur exhibits periodic appearances of wind and infall signatures in Balmer lines which tie both phenomena to a region rotating at the stellar rotation period, as would be expected in the unified Shu and collaborators model (Najita & Shu 1994; Ostriker & Shu 1995). However, the standard accretion diagnostics usually applied to later-type (K, M) TTS are not observed in this earlier (G2) TTS (veiling continuum and forbidden [O I] λ6300 emission; unpublished spectra), so that the behavior of the Balmer lines cannot be definitely linked to disk accretion activity. Further examples of periodicities synchronous with the stellar rotation period in wind and infall signatures in cTTS with better understood accretion and outflow signatures would provide clear evidence that at least one component of an accretion-driven wind originates near the disk truncation radius.

4. CONCLUSIONS

Magnetospheres must be integral components in the angular momentum evolution of young stellar objects during the phase of disk accretion. In low mass T Tauri stars which are still undergoing disk accretion and driving collimated energetic outflows, the central stars generate strong magnetic dynamos and have optically visible photospheres that reveal stars spinning an order of magnitude below break-up velocities. A picture is emerging which requires the stellar magnetosphere to couple to the disk in order to spin-down the central star. Whether the demands for angular momentum removal from the accretion disk system rely on stellar or disk magnetospheres to drive the accretion powered T Tauri outflows is still uncertain. However, since accretion/outflow associations are observed in forming stars over the full range of stellar masses, models linking the two cannot rely solely on the formation of a stellar dynamo in a fully convective star. The requisite magnetic fields, either from the central star or the disk, may thus need to originate from pre-collapse conditions. Ultimately, successful star formation models must be able to account for accretion/outflow connections and angular momentum evolution for forming stars of all masses. The T Tauri stars provide a valuable standard against which to assess accretion phenomena and angular momentum evolution in protostars.

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