Understanding the Spins of Young Stars

Sean Matt

Department of Astronomy, University of Virginia, Charlottesville VA 22904, USA

Ralph E. Pudritz

Department of Physics & Astronomy, McMaster University, Hamilton ON L8S 4M1, Canada

Abstract. We review the theoretical efforts to understand why pre-main-sequence stars spin much more slowly than expected. The first idea put forward was that massive stellar winds may remove substantial angular momentum. Since then, it has become clear that the magnetic interaction between the stars and their accretion disks explains many of the observed emission properties. The disk locking scenario, which assumes the magnetic star-disk interaction also solves the stellar spin problem, has received the most attention in the literature to date. However, recent considerations suggest that the torques in the star-disk interaction are insufficient for disk locking to explain the slow rotators. This prompts us to revisit stellar winds, and we conclude that stellar winds, working in conjunction with magnetospheric accretion, are a promising candidate for solving the angular momentum problem. We suggest future directions for both observations and theory, to help shed light on this issue.

1. Introduction: The Angular Momentum Problem for Young Stars

Before the rotation rates of optically visible pre-main-sequence stars (T Tauri stars) were known, it was expected that these stars would spin at or very near breakup speed \cite{Vogel1981}. This expectation was well-founded, since molecular cloud cores, which collapse to form stars, are observed to have \( \sim 10^4 \) times more angular momentum than a star rotating at breakup speed. Thus, collapse proceeds to first form a Keplerian disk, and stars are built up by accreting material from this disk. Even if a protostar was born with slow spin, the accretion of this disk material with high specific angular momentum would spin up the star. The timescale for an accreting star to spin up by some amount, \( \Delta f \), expressed as a fraction of breakup speed, is given by

\[
\tau_{su} \approx 10^5 \text{yrs} \left( \frac{\Delta f}{0.1} \right) \left( \frac{k^2}{0.2} \right) \left( \frac{R_t / R_*}{3} \right)^{-1/2} \left( \frac{M_*}{0.5 M_\odot} \right) \left( \frac{M_t}{5 \times 10^{-8} M_\odot/\text{yr}} \right)^{-1}, \tag{1}
\]

where \( k^2 \) is the square of the mean radius of gyration (defined by the moment of inertia \( I_* = k^2 M_* R_*^2 \)); \( R_* \) and \( M_* \) are the stellar radius and mass; \( R_t \) is the radius of the disk inner edge; \( M_t \) is the mass accretion rate; and \( f = \Omega_* R_*^{3/2} (G M_*)^{-1/2} \), where \( \Omega_* \) is the angular rotation rate of the star. Thus, a typical T Tauri star

1
should spin up by \( \approx 10\% \) of breakup speed every hundred thousand years. Since protostars are not likely born with slow spin, and since T Tauri ages are typically several times \( 10^5 \)–\( 10^6 \) yrs, one expects them to rotate rapidly.

Adding to the expectation of rapid rotation, pre-main-sequence stars contract by a factor of several times before they reach the main sequence. Furthermore, it is well known that main sequence stars with spectra type later than \( \sim F2 \) lose angular momentum via magnetized, coronal stellar winds. But the timescale for this spin down is of the order of billions of years. Since the pre-main-sequence phase lasts only a few tens of millions of years, an ordinary (main-sequence-like) stellar wind cannot be important for angular momentum evolution of a T Tauri star.

However, over the last few decades, measurements of \( v \sin i \) and rotation periods for large samples of T Tauri stars (Vogel & Kuhi 1981; Herbst et al. 2007, see Rebull et al. 2004 for a compilation) have revealed that approximately half of the stars are rotating at only \( \sim 10\% \) of breakup speed. How do these stars rid themselves of angular momentum?

2. Stellar Winds, Take One

The first proposed solution to this problem, by Hartmann & Stauffer (1989), was that substantial angular momentum could be removed by a magnetized stellar wind (see also Mestel 1984; Tout & Pringle 1992). These winds would have to be massive, with mass outflow rates comparable to the accretion rates, and the stars should be more highly magnetized than their main sequence counterparts. Hartmann et al. (1990) computed optical emission line profiles (of hydrogen, Mg II, Ca II, and Na I) expected to arise in such a wind, with a temperature \( \sim 10^4 \) K. However, these computed lines, which typically exhibit broad P-Cygni profiles, did not match very well with those observed.

As discussed in the next section, it is now clear that those lines arise primarily from material accreting onto the star (Muzerolle et al. 2001), though a small contribution to the flux from a disk wind or stellar wind might be present (Kurosawa et al. 2006). Furthermore, as discussed in section 5, the stellar winds are likely to be much hotter than \( 10^4 \) K, so the emission from the wind may be quite different than that considered by Hartmann et al. (1990).

3. The Magnetic Star-Disk Interaction

Around the same time as the work of Hartmann et al. (1990), Camenzind (1990) and Königl (1991) applied the magnetic accretion model of Ghosh & Lamb (1978) to T Tauri stars. This model was originally developed for accreting neutron stars, and it neglects any effects of a stellar wind. A common feature of all magnetic star-disk interaction models is that the stellar magnetosphere is strong enough to disrupt the accretion disk at some radius \( (R_t) \) above the surface of the star. From there, accreting material is channeled by the magnetic field lines onto the stellar surface at near free-fall velocities.

The truncation of the disk occurs where the stellar magnetosphere is able to spin down the disk material so that it is no longer centrifugally supported against gravity. Thus, the star feels a spin up torque due to the disk truncation and
subsequent accretion of material equal to the accretion rate times the specific angular momentum of material rotating at Keplerian speed at $R_t$. This accretion torque is

$$\dot{J}_a = M_a \sqrt{G M_* R_t}.$$  \hfill (2)

We used this torque to calculate the spin up time in equation 1.

This basic concept of disk truncation and magnetospheric accretion has been very successful at explaining the observed line profiles and fluxes (e.g., of hydrogen, Ca II, Na D) as arising from material that is flowing along the magnetic field line onto the surface of the star (e.g., Muzerolle et al. 2001). Also, shocks formed by accreting material striking the stellar surface provides a natural explanation for observed uv excesses and hot spots on the surface of the T Tauri stars (Königl 1991). It is now clear that magnetospheric accretion is indeed an important process occuring in accreting T Tauri stars. However, it is important to note that the observations supporting magnetospheric accretion do not address the angular momentum flow in the star-disk interaction, which is the topic of the remainder of this section.

3.1. Disk Locking

It is possible for some stellar magnetic flux to connect with the disk beyond the truncation radius, $R_t$. Due the the differential rotation between the star and disk, the magnetic field is twisted azimuthally and imparts a torque on the star. At the corotation radius, $R_{co} = f^{-2/3} R_*$, the star and disk rotate at the same angular rate. Assuming Keplerian rotation in the disk, the magnetic flux that connects the star to the region in the disk between $R_t$ and $R_{co}$ will act to spin up the star, while the flux connecting to the disk outside $R_{co}$ will remove angular momentum from the star.

In order to address the angular momentum problem, the Ghosh & Lamb (1978) model assumes that the stellar dipole magnetic field connects to the surface of the disk over a large range of radii. This provides a possible explanation for angular momentum loss, as long as there is a substantial amount of stellar magnetic flux that connects to the disk outside $R_{co}$, and $R_t$ needs to be very close to $R_{co}$. This way, the torque on the star associated with the magnetic connection to the disk can be negative and possibly strong enough to counteract the spin up torque from accretion (eq. 2).

Adopting the Ghosh & Lamb framework, a few authors (Cameron & Campbell 1993; Armitage & Clarke 1996; Pinzón 2006) have followed the spin evolution of pre-main-sequence stars according to the angular momentum equation

$$I_\ast \frac{\partial \Omega_\ast}{\partial t} = -\Omega_\ast \frac{\partial I_\ast}{\partial t} + \dot{J}_a + \dot{J}_m,$$  \hfill (3)

where $\dot{J}_m$ is the total torque due to the twisting of the connected stellar magnetic flux. Stellar models provide information about the rate of change of the stellar moment of inertia, $\partial I_\ast / \partial t$. Regardless of the choice of initial stellar spin rate, these authors find that, under most circumstances, the system evolves to a state in which the net torque on the star is very nearly zero within a timeframe of a few hundred thousand years (as expected from eq. 1).
The spin rate of the star in this torque equilibrium state can be calculated directly from the Ghosh & Lamb model, which gives

$$\Omega^\text{eq}_* = CM_\text{a}^{3/7} (GM_*)^{5/7} \mu^{-6/7},$$  \hspace{1cm} (4)

where $C$ is a constant (“fudge factor”) of order unity, $\mu \equiv B_* R_*^3$ is the dipole moment, and $B_*$ is the magnetic field strength at the surface of the star. In this state, the truncation radius must be very close to the corotation radius. Thus, the stellar rotation rate is very nearly the same as that at the disk inner edge, and this is referred to as the “disk locked” state.

There are several models in the literature that follow similar assumptions as the Ghosh & Lamb model. Each of these differ in the details of how they treat the magnetic coupling between the stellar field and the disk (see Matt & Pudritz 2005b). In the end, they all derive the same formula (4), but with slightly different values of the factor $C$ of order unity. For example, Königl (1991) used $C \approx 1.15$.

The X-wind (Shu et al. 1994 and subsequent works) is a disk locking model that removes the excess angular momentum by means of a wind from the inner edge of the disk. To do this, the X-wind assumes the stellar dipole magnetic field lines are pinched and connect to a very small region (the “X-point”) around $R_\text{co}$, rather than connecting to a large portion of the disk. Also, the X-wind assumes a torque equilibrium state, rather than producing a general formulation for a spin up or spin down state. Because it is a disk locking model, the X-wind predicts the same equilibrium spin as in equation (4), with its own factor $C$ of order unity. Ostriker & Shu (1995) found $C \approx 1.13$.

We can use equation (4) to predict the stellar dipole field strength necessary to explain the existence of slow rotators,

$$B_\text{eq}^* \approx 900 \text{ Gauss} \left( \frac{C}{1.0} \right)^{7/6} \left( \frac{f}{0.1} \right)^{-7/6} \times \left( \frac{R_*}{2R_\odot} \right)^{-5/4} \left( \frac{M_*}{0.5M_\odot} \right)^{1/4} \left( \frac{\dot{M}_\text{a}}{5 \times 10^{-8} M_\odot/\text{yr}} \right)^{1/2},$$  \hspace{1cm} (5)

It is evident that the Ghosh & Lamb-type and the X-wind disk locking models require stellar field strengths of the order of a kilo-Gauss (eq. 5; see Johns-Krull et al. 1999b). Furthermore, disk locking always requires a large amount of stellar flux to connect to the disk.

3.2. Problems With Disk Locking

Kilo-Gauss fields were in fact a prediction of disk locking (Königl 1991). So when kilo-Gauss strength mean fields were first observed in T Tauri stars (e.g., Basri et al. 1992; Guenther 1997; Johns-Krull et al. 1999b), this seemed to be evidence for disk locking. However, these magnetic field measurements do not probe the global, dipole field strength (e.g., Safier 1998; Johns-Krull et al. 1999a), required for efficient angular momentum loss. Rather, spectropolarimetric observations of a handful of accreting T Tauri stars to date (see contribution by Johns-Krull in these proceedings) reveal upper limits or marginal detections of the global field of $\sim 100$ Gauss. This is a serious problem for understanding
the existence of the slow rotators, since for these field strengths, equation (4) predicts spin rates in excess of 50\% of breakup.

A second and independent problem with the disk locking scenario regards the need for lots of stellar flux to connect to the disk. Safier (1998) pointed out that stellar winds should open (disconnect from the disk) all of the stellar flux reaching outside \( \sim 3R_\star \), affecting all disk locking models. Alternatively, several authors (Lynden-Bell & Boily 1994; Lovelace et al. 1995; Agapitou & Papaloizou 2000; Uzdensky et al. 2002) showed that differential rotation between the star and disk will lead to an opening of much of the field that is assumed closed in the Ghosh & Lamb model. In particular, Uzdensky et al. (2002) showed that the magnetic connection between the star and disk becomes severed when the magnetic field is twisted to a point where \( B_\phi/B_z \) is greater than one, where \( B_z \) is the vertical vector component of the field, and \( B_\phi \) is the azimuthal component generated by the twisting.

This amount of twisting occurs in approximately one half orbit of the disk, indicating that a large scale magnetic connection between the star and disk cannot persist for long. The only way for the magnetic field to remain connected to the disk is for the magnetic field to “slip” through the disk (e.g., via turbulent diffusion or magnetic reconnection) at a rate equal to the differential rotation rate, so that \( B_\phi/B_z \) remains small. The slip rate of the magnetic field relative to the disk depends on the physics of the magnetic coupling to the disk. Matt & Pudritz (2005b) characterized this coupling with a parameter \( \beta \), such that the slip rate of the magnetic field through the disk equals \( \beta(B_\phi/B_z)v_K \),

Figure 1. The factor \( C \) in equation (4) as a function of the magnetic coupling parameter \( \beta \) quantifies the effect of field line opening. The dashed line corresponds to the value of \( C = 1.15 \) used by Königl (1991). The figure is adapted from Matt & Pudritz (2005b).
where \( v_K \) is the Keplerian speed. Thus, large \( \beta \) corresponds to weak magnetic coupling (fast slipping), and small \( \beta \) means strong coupling.

Matt & Pudritz (2005b) quantified the effect that the field opening has on the torque felt by the star. To do this, they followed the assumptions of Ghosh & Lamb (1978) except that the torque was set to zero where \( B_\phi/B_z \) exceeds unity, corresponding to where the magnetic field is expected to open. They were able to derive equation (4) such that the factor \( C \) is a function of \( \beta \) and contains all the effects of field opening. The solid line in figure 1 shows this factor \( C \) as a function of \( \log \beta \). For reference, the dashed line indicates the value of \( C \) used by König (1991).

The behavior of \( C(\beta) \) can be understood as follows. In the strong coupling limit \( (\beta \ll 1) \), the field becomes more open as the coupling gets stronger; so the spin-down torque decreases with \( \beta \), and this means the equilibrium spin rate increases. In the weak coupling limit \( (\beta \gg 1) \), the magnetic field is more connected, but the slip rate of the field is faster; so the field is less twisted for increasing \( \beta \), and so the spin-down torque decreases with increasing \( \beta \). Assuming the slipping or diffusion of the magnetic field is comparable to the effective viscosity in the disk (e.g., in an \( \alpha \)-disk; Shakura & Sunyaev 1973), Matt & Pudritz (2005b) estimated that the likely value of \( \beta \) in T Tauri systems is \( \sim 10^{-2} \). From figure 1 and equation (4), this value of \( \beta \) predicts an equilibrium spin rate more than 10 times faster than predicted by the Ghosh & Lamb model. Matt & Pudritz (2005b) concluded that, when the effect of the field opening is taken into account, the slowly rotating T Tauri stars cannot be explained by a disk locking scenario.

4. Stellar Winds, Reincarnated

The problems with disk locking, and the expectation that the stellar magnetic field will be largely open, prompts us to revisit the suggestion by Hartmann & Stauffer (1989) that stellar winds from T Tauri stars can remove substantial angular momentum. Since stellar winds were first proposed, however, we have gained a more detailed picture of the star-disk interaction. In particular, we now know that much of the emission properties of T Tauri stars arise from magnetospheric accretion phenomena. So now a more complete picture of the interaction between the star and disk, including the transport of angular momentum by a stellar wind, is presented in figure 2.

In the simplest case, the star is magnetically connected only to the inner edge of the disk and experiences only a spin up torque from this interaction (namely, the accretion torque, eq. [2]). The stellar wind extracts angular momentum at a rate (e.g. Weber & Davis 1967; Mestel 1984)

\[
\dot{J}_w = -\dot{M}_w \Omega_* r_A^2,
\]

where \( \dot{M}_w \) is the mass outflow rate in the stellar wind alone and \( r_A \) is the radius where the flow speed equals the magnetic Alfvén wave speed. Note that, strictly speaking, the wind is 3-dimensional, so the value of \( r_A^2 \) in equation (6) actually represents the mass-loss weighted average of \( r_A^2 \) over a 3-dimensional Alfvén surface.
Assuming the system will evolve to a state with a very low net torque, we can combine equations (2) and (6) to find the equilibrium spin rate (Matt & Pudritz 2005a), expressed as a fraction of breakup speed,

\[ f_{eq} \approx 0.1 \left( \frac{r_A/R_s}{12} \right)^{-2} \left( \frac{\dot{M}_w/\dot{M}_a}{0.1} \right)^{-1} \left( \frac{R_t/R_s}{3} \right)^{1/2}. \] (7)

So the existence of slow rotators can be explained, if the Alfvén radius is comparable to the solar value (for the sun \( r_A \approx 12R_s \); Li 1999), and the mass outflow rate in the stellar wind is a substantial fraction of the accretion rate. The latter requires a lot of energy to drive the wind. Matt & Pudritz (2005a) suggested the wind is driven energetically by accretion power and showed that of the order of 10% of the accretion power is needed.

This scenario holds that substantial angular momentum loss occurs only while the stellar wind is significantly enhanced by accretion power. Thus there should be a link between a slow equilibrium spin and accretion (proposed by Edwards et al. 1993). Rebull et al. (2004, and see contribution by Rebull in these proceedings) showed that such a link might account for the evolution of the distribution of T Tauri star spins, observed to vary from cluster to cluster.
5. The Nature of Accretion Powered Stellar Winds

It seems now that, after being largely neglected for \(~ 15\) years, a stellar wind may still be a promising candidate for solving the angular momentum problem for young stars. However, more theoretical work and observations will be necessary to understand the true nature and importance of T Tauri star winds. Here is what we can say thus far.

Large-scale flows with mass outflow rates comparable to \((\sim 10\% \text{ of})\) the accretion rates do emanate from these systems (e.g., Reipurth & Bally [2001]). It is clear that much of this flow originates from the disk (Blandford & Payne [1982]; Shu et al. [1995]), but it is not yet clear what fraction of the total flow can originate from the star. The best estimate to date is from Decampli (1981), who showed that the outflow rates of stellar coronal winds with temperatures of \(\approx 10^6 \text{ K}\) cannot exceed \(10^{-9} M_\odot \text{ yr}^{-1}\), or else the X-ray luminosity from the wind would exceed observed values. For now, we simply emphasize that a wind from the disk provides the best explanation for the bulk of the large-scale outflow, while the primary importance of the stellar wind may be to remove angular momentum from the star. Figure 2 illustrates both wind components.

T Tauri stars are magnetically active and possess hot coronae that are 4–5 orders of magnitude more energetic than the solar corona (Feigelson & Montmerle [1999]). Therefore, it seems reasonable to assume that T Tauri stars possess a thermally driven wind, like a scaled-up (in \(\dot{M}_w\) and \(B_*\)) solar coronal wind. The wind temperature required for thermal driving scales proportional to the square of the escape speed from the star (Parker [1958]). This means that for a typical T Tauri star with \(M_* = 0.5 M_\odot\) and \(R_* = 2 R_\odot\), the temperature at the base of the stellar wind should be \(\approx 300,000 \text{ K}\). This is much cooler than the \(10^6 \text{ K}\) used by Decampli (1981), and so the mass outflow rate can be much higher than \(10^{-9} M_\odot \text{ yr}^{-1}\) before the X-ray emission becomes a problem. We have computed a number of magnetic coronal winds for T Tauri stars and found viable solutions to equation (7) to explain the slow rotators (Matt & Pudritz 2007, in preparation). The way in which accretion power transfers to heat the stellar corona is yet unknown, though it likely would involve the dissipation of magneto-acoustic waves and/or mixing of shock-heated accreting gas into the stellar wind.

Edwards et al. (2003, 2006) observed the He I 10830 line in several accreting T Tauri stars. In many cases, they found broad P-Cygni profiles similar to the hydrogen line profiles predicted by the stellar wind models of Hartmann et al. (1999, see §2). A stellar wind, as opposed to a disk wind, provides the best explanation for the large range of blue-shifted velocities over which the line is absorbed. Dupree et al. (2005) observed the He I 10830 line, as well as uv lines of C III and O VI, in two systems and concluded that the stellar wind had a temperature of \(\sim 300,000 \text{ K}\). Observations such as these are important for our understanding of the nature of T Tauri stellar winds.

6. Challenges

Here we list just a few of the most important outstanding questions for understanding the angular momentum loss in young stars.
What are the mass outflow rates of the stellar winds (as distinct from the disk wind) in accreting T Tauri stars? What is the temperature of these winds? For this, radiative transfer modeling including stellar winds, disk winds, and accretion flow will be useful. Also, magnetic field measurements that gauge the strength of the global (dipole) component of the field are crucial to quantify the strength of magnetic torques.

Can we understand the observed distributions of T Tauri star spins, and evolution of the distributions, in the context of an accretion-powered stellar wind model, in a similar way as has been done for the disk locking scenario (as discussed by Rebull, these proceedings)? How does accretion power transfer to the stellar wind? Is it thermally driven or otherwise? What emission properties are expected from an accretion-powered stellar wind?

Answers to many of these questions are already being pursued by a number of research groups. We are optimistic that the combination of precision spectroscopy and advanced numerical simulations and theoretical work will bring many new insights to the solution of one of the most interesting and difficult problems in stellar astrophysics.

Acknowledgments. We would like to thank the organizers for a fun and productive workshop, and this work benefited from discussions with numerous attendees (including Gibor Basri, Steve Cranmer, Andrea Dupree, Lee Hartmann, Chris Johns-Krull, Luisa Rebull, Jeff Valenti, and Sidney Wolff). Sean Matt acknowledges support from the University of Virginia through a Levinson/VITA Fellowship, partially funded by The Frank Levinson Family Foundation through the Peninsula Community Foundation.

References

Agapitou, V., & Papaloizou, J. C. B. 2000, MNRAS, 317, 273
Armitage, P. J. & Clarke, C. J. 1996, MNRAS, 280, 458
Basri, G., Marcy, G. W., & Valenti, J. A. 1992, ApJ, 390, 622
Blandford, R. D. & Payne, D. G. 1982, MNRAS, 199, 883
Camenzind, M. 1990, in Reviews in Modern Astronomy, ed. G. Klare, 234–265
Cameron, A. C. & Campbell, C. G. 1993, A&A, 274, 309
Decampli, W. M. 1981, ApJ, 244, 124
Dupree, A. K., Brickhouse, N. S., Smith, G. H., & Strader, J. 2005, ApJ, 625, L131
Edwards, S., Fischer, W., Hillenbrand, L., & Kwan, J. 2006, ApJ, 646, 319
Edwards, S., Fischer, W., Kwan, J., Hillenbrand, L., & Dupree, A. K. 2003, ApJ, 599, L41
Edwards, S., Strom, S. E., Hartigan, P., Strom, K. M., Hillenbrand, L. A., Herbst, W., Attridge, J., Merrill, K. M., Probst, R., & Gatley, I. 1993, AJ, 106, 372
Feigelson, E. D. & Montmerle, T. 1999, ARA&A, 37, 363
Ghosh, P. & Lamb, F. K. 1978, ApJ, 223, L83
Guenther, E. W. 1997, in IAU Symp. 182: Herbig-Haro Flows and the Birth of Stars, ed. B. Reipurth & C. Bertout, 465–474
Hartmann, L., Avrett, E. H., Loeser, R., & Calvet, N. 1990, ApJ, 349, 168
Hartmann, L. & Stauffer, J. R. 1989, AJ, 97, 873
Herbst, W., Eisloffel, J., Mundt, R., & Scholz, A. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil, 297–311
Johns-Krull, C. M., Valenti, J. A., Hatzes, A. P., & Kanaan, A. 1999a, ApJ, 510, L41
Johns-Krull, C. M., Valenti, J. A., & Koresko, C. 1999b, ApJ, 516, 900
Konigl, A. 1991, ApJ, 370, L39
Kurosawa, R., Harries, T. J., & Symington, N. H. 2006, MNRAS, 370, 580
Li, J. 1999, MNRAS, 302, 203
Lovelace, R. V. E., Romanova, M. M., & Bisnovatyi-Kogan, G. S. 1995, MNRAS, 275, 244
Lynden-Bell, D. & Boily, C. 1994, MNRAS, 267, 146
Matt, S. & Pudritz, R. E. 2005a, ApJ, 632, L135
—. 2005b, MNRAS, 356, 167
Mestel, L. 1984, LNP Vol. 193: Cool Stars, Stellar Systems, and the Sun, 193, 49
Muzerolle, J., Calvet, N., & Hartmann, L. 2001, ApJ, 550, 944
Ostriker, E. C. & Shu, F. H. 1995, ApJ, 447, 813
Parker, E. N. 1958, ApJ, 128, 664
Pinzón, G. 2006, Ph.D. Thesis, Astronomy, Observatório Nacional, Brazil
Rebull, L. M., Wolff, S. C., & Strom, S. E. 2004, AJ, 127, 1029
Reipurth, B. & Bally, J. 2001, ARA&A, 39, 403
Saifer, P. N. 1998, ApJ, 494, 336
Shakura, N. I. & Sunyaev, R. A. 1973, A&A, 24, 337
Shu, F., Najita, J., Ostriker, E., Wilkin, F., Ruden, S., & Lizano, S. 1994, ApJ, 429, 781
Shu, F. H., Najita, J., Ostriker, E. C., & Shang, H. 1995, ApJ, 455, L155
Tout, C. A. & Pringle, J. E. 1992, MNRAS, 256, 269
Uzdensky, D. A., Königl, A., & Litwin, C. 2002, ApJ, 565, 1191
Vogel, S. N. & Kuhi, L. V. 1981, ApJ, 245, 960
Weber, E. J. & Davis, L. J. 1967, ApJ, 148, 217