MAGNETOSPHERICALLY MEDIATED ACCRETION IN CLASSICAL T TAURI STARS

Paradigm for Low Mass Stars Undergoing Disk Accretion?

S. EDWARDS
Smith College
Northampton, MA 01063, USA

Abstract. Observational evidence suggests that disk accretion in low mass stars is mediated by the stellar magnetosphere in the inner few stellar radii of a star/accretion disk system. A strong stellar field appears to disrupt the inner disk and channel accreting material in a funnel flow toward the stellar surface. It is possible that coupling between the stellar magnetosphere and the inner accretion disk plays a profound role in the evolution of a forming star, regulating its spin, establishing its initial angular momentum, and launching the ubiquitous accretion-driven outflows which are the subject of this symposium. Although the evidence that forming low mass stars undergo magnetospherically mediated accretion is considerable, there are a growing number of challenges to this paradigm which require close observational scrutiny.

1. Introduction

You may be wondering why a contribution on magnetospheric accretion has been included in a symposium on Herbig-Haro Flows. There are two compelling reasons. One is that two classes of models use open stellar field lines to launch energetic winds from disk-accreting stars, either from the magnetosphere-disk interface (Shu & Shang, this volume) or from the magnetospheric foot-points on the stellar surface (Camenzind, this volume). The second reason is that it is important to understand which spectroscopic features diagnose the presence of magnetospheric accretion in classical T Tauri stars (cTTS) in order to assess, as near-infrared high resolution spectra become available, whether magnetospheres are important in the more deeply embedded Class I sources (Lada and Wilking, 1984) driving outflows.

B. Reipurth and C. Bertout (eds.), Herbig–Haro Flows and the Birth of Low Mass Stars, 433–442.

Low mass stars first become optically visible as T Tauri stars at an age $t \sim 1$ Myr, at which time approximately half are still surrounded by accretion disks (Strom, Edwards and Skrutskie 1993). Disk accretion rates for cTTS, inferred primarily from optical continuum emission excesses are typically $\dot{M}_{acc} \sim 10^{-7}$ $M_{\odot}$ yr^{-1} (Hartigan, Edwards and Ghandour [HEG], 1995; but see Hartmann this volume). These active young stars also likely generate strong dynamo magnetic fields on the order of 500 to 1500 kG (Guenther, this volume; Montmerle et al., 1993; Basri, Marcy and Valenti, 1992.) which are capable of coupling to the accretion disk and disrupting it within a few stellar radii of the central star (Königl 1991).

There is mounting evidence that magnetosphere-disk coupling plays a vital role in the angular momentum evolution of forming stars, making it essential that the relevance of this mechanism be firmly established. Key areas where magnetosphere-disk coupling may be important are:

- magnetosphere-disk coupling may account for the apparent regulation of the angular velocity of the central star in the presence of disk accretion, countering its tendency to spin up, both from accretion of disk material of high specific angular momentum and from contraction toward the main-sequence (Edwards et al. 1993; Bouvier et al. 1993; Cameron and Campbell, 1993; Ghosh, 1995).

- magnetosphere-disk coupling has the potential to produce a broad dispersion in angular velocities among low mass stars on the ZAMS, if the timescale for disk dissipation extends over timescales from less than 1 Myr up to 10 Myr (Bouvier 1994; Cameron, Campbell and Quaintrell, 1995; Bouvier et al. 1997).

- magnetosphere-disk coupling may not only extract angular momentum from the star, braking its spin; but also may expel this angular momentum from the system via an accretion driven wind using open stellar field lines for a magnetocentrifugal fling (Najita and Shu, 1994).

While details of how the T Tauri magnetosphere couples to the inner accretion disk are not yet established, most investigators agree that the disk will be disrupted somewhere in the vicinity of the co-rotation radius, and the accretion flow will be redirected to free-fall toward the star in a magnetic *funnel flow* (Königl 1991; Hartmann, Hewett and Calvet 1994; Ostriker and Shu, 1995; Paatz and Camenzind 1996; Li, Wickramasinghe and Ruediger, 1996). This paper will review the evidence for funnel flows, and describe some complexities and challenges to this paradigm.

2. Observational Evidence for Magnetospheric Accretion

2.1. SUPPORT FOR FUNNEL FLOWS

Several aspects of cTTS activity are often cited as providing empirical support for the prevalence of magnetically channeled funnel flows:

1. *Kinematic evidence for mass infall at free-fall velocities:* Sensitive spectroscopic surveys of cTTS reveal a high frequency of inverse P Cygni features in hydrogen and permitted metallic lines (Edwards et al. 1994; Najita, Carr, and Tokunaga 1996) with redshifted absorption components indicating infall along the line of sight at velocities comparable to those expected from magnetospheric accretion funnels (Calvet and Hartmann, 1992).

2. *Broad, asymmetric, and centrally peaked hydrogen emission line profiles:* Radiative transfer models of hydrogen lines in a schematic funnel flow can reproduce many peculiarities of the observed H line morphology, suggesting that cTTS emission lines are formed predominantly in accretion flows, not in a wind (Hartmann, Hewett and Calvet 1994; Calvet, this volume). Recent multi-level calculations (Muzerolle, Calvet and Hartmann, in prep.) have successfully reproduced Balmer, Paschen, and Brackett line luminosities as well profile shapes.

3. *Near infrared colors:* Spectral energy distributions of cTTS between 1-5μ are not well fit by a simple combination of a stellar photosphere and a standard accretion disk model; better fits are achieved if the inner disks are truncated with hole sizes about 70% of the co-rotation radius (Bertout, Basri and Bouvier 1988; Kenyon, Yi and Hartmann, 1996; Meyer, Calvet and Hillenbrand 1997). Truncation radii at or inside co-rotation are necessary to allow the accretion flow to fall toward the star.

4. *Periodic photometric modulation from hot spots:* Multiwavelength photometric monitoring reveals that while rotational modulation from many T Tauri stars can be attributed to large cool starspots, some cTTS also reveal signatures of spots hundreds to thousands of degrees hotter than the photosphere (Bouvier et al. 1993; Bertout et al. 1996). These can be accounted for by non-axially symmetric funnel flows if the rotation and magnetic axes are not aligned, allowing accretion shocks on the stellar surface to rotate out of view (Bertout 1989).

5. *Periodic spectroscopic signature of infall and/or outflow?* Time series analysis has revealed one T Tauri star, SU Aur, with periodicity in the absorption strength of both a wind and an infall feature that vary 180° out of phase relative to each other, with a period equal to the rotation period of the star (Johns and Basri 1995a; Petrov et al. 1996). This behavior is consistent with a non-aligned magnetosphere launching both a wind and an accretion flow from the "x-point", which changes its aspect relative to

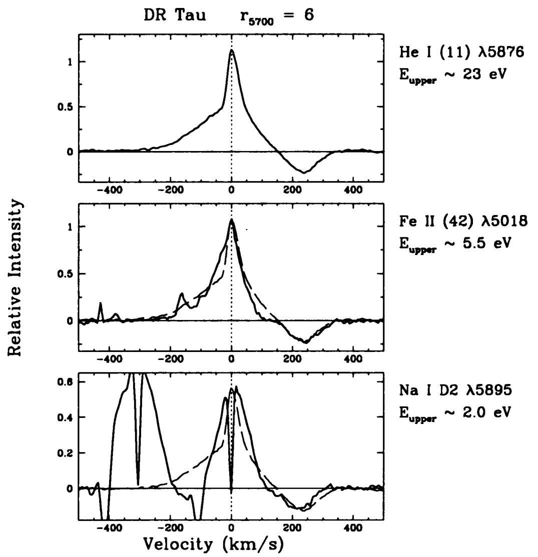

Figure 1. Simultaneous residual line profiles in the high accretion rate cTTs DR Tau. Lines expected to form in very different zones of a magnetic accretion funnel are seen to have nearly identical redshifted absorption. For reference, the normalized He I profile is superposed on the Fe II and Na D2 profile. Intensity is relative to the continuum.

the observer (Shu et al. 1994). Unfortunately this star lacks the definitive signatures for disk accretion that identify classical T Tauri stars among lower mass objects – optical continuum veiling and [O I] λ6300 forbidden emission (HEG) – making the interpretation of these intriguing periodicities unclear.

2.2. CHALLENGES TO FUNNEL FLOWS

While the above phenomena provide strong support for magnetospherically mediated accretion in cTTS, a closer look reveals a complexity that challenges any simple picture of magnetosphere-disk coupling:

1. Some cTTS show very similar inverse P Cygni profiles among lines covering a surprising range of excitation energies, from a low of 2 eV at NaD to a high of 23 eV at He I, as shown in Figure 1. This is not easily explained by current models of the thermal structure of magnetic accretion funnels where the temperature is predicted to increase toward the star due to compressional heating (Martin 1996), with lower excitation lines formed at the base of the flow and higher excitation lines formed near the accretion shock (Martin 1997).

2. Inner disk truncation radii determined from modelling near infrared spectral energy distributions must be viewed with caution. Models to date are relatively simple and do not take into account possible heating of the inner disk from magnetic effects, which can lead to underestimates of the hole sizes (Armitage and Clark 1996).

3. Spectral time series analysis has not revealed periodic behavior in lines or veiling among cTTS that possess definitive accretion signatures, despite considerable time coverage on about 10 stars (Johns and Basri 1995b; Gullbring et al. 1996; Johns-Krull and Basri, 1997). Instead, the H lines are seen to undergo stochastic variations in velocity intervals of 50 to 100 $km\ s^{-1}$ that vary independently of each other, and veiling variations are not well correlated with line variations. This complexity, combined with the fact that luminosities from photometrically derived hot spots are typically only a few percent of the spectroscopically derived veiling luminosity (Bertout et al. 1996), suggests that complex magnetic geometries rather than coherent dipole structures control the accretion flow.

4. Periods of hot spots diagnosed from broad-band photometric studies are observed to vary by up to 25% (Bouvier et al. 1995). Although the reality of this claim has been challenged by Herbst and Wittenmyer (1997), if real, it is not easily accounted for in magnetospheric accretion scenarios (Bertout et al. 1996).

Taken together, the above considerations reveal that our knowledge of magnetic funnel flows in cTTS is superficial, and considerable study is required to achieve the next level of understanding.

3. Permitted Metallic Lines as Funnel Flow Diagnostics?

Emission lines of hydrogen are the strongest features in cTTS spectra. Success in reproducing the general morphology and luminosity of H lines with magnetospheric accretion models lends considerable support to a funnel flow origin for these lines (see Calvet, this volume). However, the optical and near infrared spectra of cTTS also include a rich array of permitted metallic emission lines, which offer additional probes of the near-stellar environment in accretion disk systems. Evidence that lines of He I, Ca II, Mg I, Fe I,II and Si I derive from accretion activity comes from correlations between line strength and accretion diagnostics such as continuum veiling and near infrared excesses, as illustrated in Figure 2.

A growing body of evidence supports the conclusion that the permitted metallic lines originate in *two distinct regimes* characterized by differing kinematic and physical conditions. These lines are typically one to two hundred $km\ s^{-1}$ narrower than H lines in the same star (Edwards et al. 1994) and are characterized by a two component structure, consisting of a

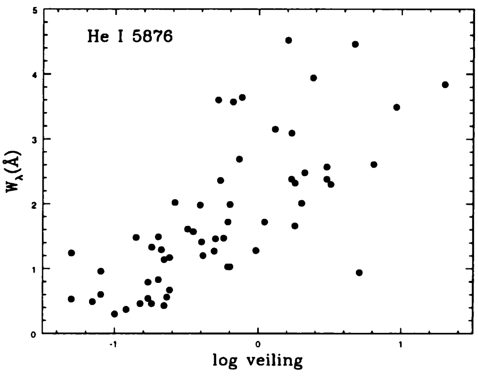

Figure 2. Emission equivalent widths for He I λ5876 for 61 spectra of 30 cTTS from the sample in HEG plotted against the veiling, defined as the ratio of the excess continuum flux to the stellar photosphere.

broad (BC; ≥ 100 $km\ s^{-1}$) and a narrow (NC; < 50 $km\ s^{-1}$) component (Hamann and Persson 1992; Batalha et al. 1996).

An illustration of this morphology is given in Figure 3, which also shows that the relative proportion of BC to NC emission varies considerably among cTTS, ranging between the two extreme cases where the profile is dominated by only one of the two components. Although there is no clear pattern of profile morphology with accretion diagnostics, two-component fits of Gaussian shapes to He I λ5876 profiles in 61 spectra of 30 cTTS reveal that the parameters of the NC are remarkably consistent among the entire sample of stars, with full width at half maxima $\sim$ 48 $km\ s^{-1}$ and centroid velocities at rest relative to the stellar velocity (Beristain, Edwards, Kwan, and Hartigan, 1997; BEKH). The BC is less consistent, ranging in FWHM from 150 to 300 $km\ s^{-1}$, and centroid velocities blueshifted relative to the star by up to 50 $km\ s^{-1}$ in about 1/3 of the sample. Examples of fits to the two kinematic components are illustrated in Figure 4, which also shows that an individual cTTS can transition from metallic lines dominated by BC emission to the opposite on a timescale of weeks, with no correlation with veiling.

Additional evidence that the NC and BC arise in two physically distinct regimes comes from a detailed analysis of unblended Fe I lines (2.5-6 eV) and Fe II lines (5-6 eV) in the active cTTS DR Tau (BEKH). This study demonstrates that a systematic increase in the FWHM of Fe lines from 20 to 80 $km\ s^{-1}$ with increasing line strength is accounted for by differing proportions of NC to BC emission. All Fe lines can be decomposed into two Gaussian contributions with *identical* kinematic components, but stronger

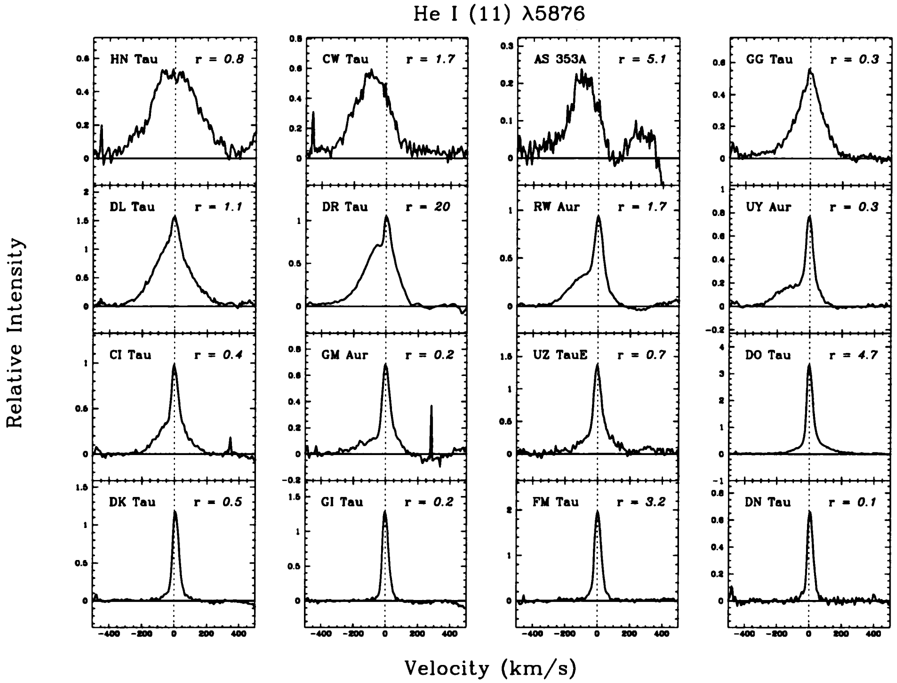

Figure 3. Residual He I λ5876 profiles for 12 cTTS illustrating the variety of relative contributions from the broad component and the narrow component. Profiles are ordered by line width, from broadest to narrowest. Intensity is in units of the continuum.

Fe lines are characterized by a larger contribution from BC relative to NC emission. The simplest explanation of this behavior is that the densities and temperatures of the BC and NC regions are sufficently dissimilar to give rise to Fe lines with differing relative intensities.

It will be important to clarify the origin of each kinematic component in order to fully understand the star-disk interface region. The large line widths of the BC, the tendency for it to be blueshifted, and occasionally to show inverse P Cygni structure, are consistent with this component arising in the magnetospheric accretion flow. In contrast, the NC appears to arise in a region which is hotter and optically thicker than the BC (BEKH), is at rest with respect to the star, and can vary independently of the BC (Gullbring et al., 1996). The near-photospheric line widths of the NC suggest formation on the stellar surface rather than in a Keplerian disk, possibly in the postshock region at the base of accretion flow (Batalha et al., 1996). Additional support for this possibility comes from CIV line profiles in cTTS, which also show strong NC emission and must arise in a region $T \sim 10^5$ K

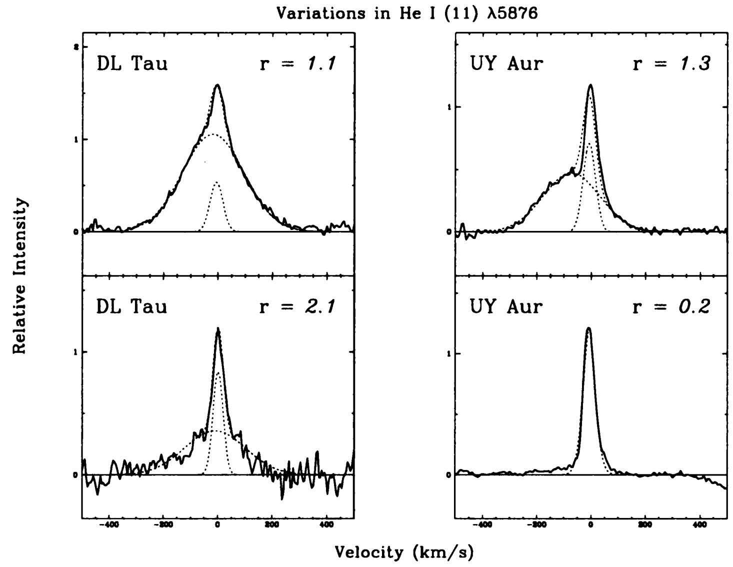

Figure 4. Residual He I λ5876 profiles for 2 cTTS illustrating two component Gaussian fits, which separate the NC and BC contributions. Variations in the relative proportion of NC to BC emission in the same star do not correlate with veiling (r).

(Calvet et al., 1996). If this interpretation is correct, the NC will be a crucial diagnostic of the energetics of the final transfer of mass and angular momentum of material accreting from the disk to the stellar surface.

4. Discussion and Future Prospects

The observational evidence for magnetic funnel flows in disk accreting cTTS is strong, but our understanding of this complex region is still primitive. Most important is the need to establish the relevance of this region to the angular momentum evolution of forming stars. *Is magnetosphere-disk coupling the mechanism which establishes the initial angular momentum of a star?* While the evidence supporting this possiblity is tantalizing, much larger statistical samples of rotation periods of accreting and post-accreting stars must be accumulated. Alternative spin-down mechanisms for accreting stars are being proposed (Popham 1996), and need to be subjected to empirical tests. *Are the accretion-driven winds which characterize all forming stars launched with open field lines from the stellar magnetosphere?* Until definitive observational signatures of the wind origin are identified, the answer to this fundamental question remains uncertain.

The quest to determine the role of the stellar magnetosphere in govern-

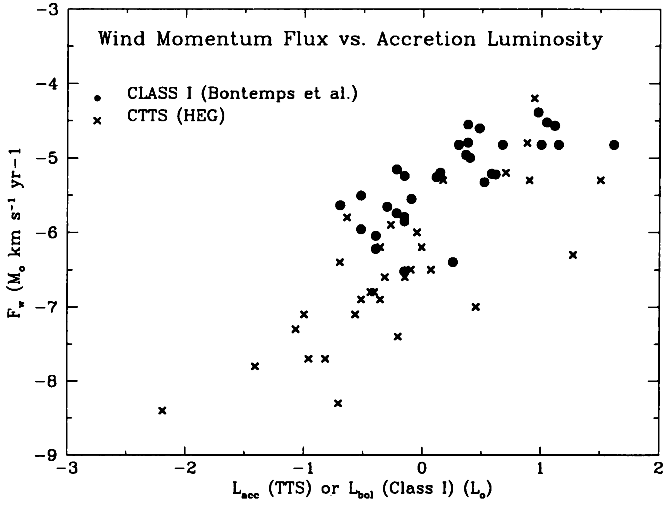

Figure 5. The wind momentum flux plotted against accretion luminosity for two groups of low mass stars. For the Class I sources the wind momentum is determined from $^{12}CO(2-1)$ IRAM data and the bolometric luminosities are assumed to be dominated by accretion (Bontemps et al. 1996). For the cTTS the wind momentum is determined from the high velocity component of the [O I]λ6300 line and the luminosities are the accretion luminosities determined from the veiling flux (HEG).

ing the angular momentum evolution of forming stars also requires scrutiny of the precursors to the optically visible cTTS. Comparison of the overall energetics between cTTS and the more deeply embedded Class I sources suggests a unity of accretion/outflow phenomena. This is illustrated in Figure 5, which shows a similar relation between wind momentum and accretion luminosity for both groups of objects. The advent of high resolution near infrared spectroscopy will allow us to probe this comparison further, making it possible to study the near-stellar regions in Class I sources and to determine the importance of magnetosphere-disk interactions during this earlier stage of star formation.

Acknowledgements: I thank Georgina Beristain for assistance in preparing the figures for this manuscript. Pat Hartigan was instrumental in data reduction and determination of veiling and residual profiles shown here. I also thank Nuria Calvet, Lee Hartmann, John Kwan, James Muzerolle, and Steve Strom for valuable conversations, suggestions, and inspirations.

References

Armitage, P.J. and Clarke, C.J.: 1996, MNRAS, 280, 458

Basri, G., Marcy, G. W., and Valenti, J.A.: 1992, ApJ 390, 622

Batalha, C.C., Stout-Batalha, N.M., Basri, G. and Terra, M.A.O.: 1996, ApJS 103, 211

Beristain, G., Edwards, S., Kwan, J., and Hartigan, P.: 1997, in preparation [BEKH]

Bertout, C.: 1989, ARAA, 27, 351

Bertout, C., Basri, G., and Bouvier, J.: 1988, ApJ 330, 350

Bertout, C., Harder, S., Malbet, F., Mennessier, C., and Regev, O.: 1996, AJ, 112, 2159

Bouvier, J., Cabrit, S., Fenandez M., Martin, E., Matthews, J. 1993, A&A, 101, 495

Bouvier, J.: 1994, in *The Eighth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, ed. J.P. Caillaut, APS Conf Series, 64, 51

Bouvier, J. et al.: 1997, A&A, 318, 495

Bontemps, S., André, P., Terebey, S. and Cabrit, S.: 1996, A&A, 311, 858

Calvet, N, and Hartmann, L. 1992, ApJ, 386, 239

Calvet, N., Hartmann, L., Hewett, R., Valenti, J., Basri, G., and Walter, F., 1996 in *ASP Conf. Proc. 109; Cool Stars, Stellar Systems and the Sun*, eds. R. Pallavicini and A. Dupree, (San Francisco: ASP), 419

Cameron, A., Campbell, C.: 1993; A&A, 274, 309

Cameron, A., Campbell, C., Quaintrell, H.: 1995, A&A, 298, 133

Edwards, S., Strom, S., Hartigan, P., Strom, K., Hillenbrand, L., Herbst, W.Attridge, J., Merrill, M., Probst, R.,and Gatley, I.: 1993, AJ, 106, 372

Edwards, S., Hartigan, P., Ghandour, L., and Andrulis, C.: 1994, AJ, 108, 1056

Ghosh, P.: 1995, MNRAS, 272,763

Ghosh, P. and Lamb, F.: 1979, ApJ, 234, 296

Gullbring, E., Petrov, P.P., Ilyn, I., Tuominen, I., Gahm, G.F. and Loden, K.: 1996, A&A, 314, 835

Hamann, F. and Persson, S.E.: 1992, ApJS 82,287

Hartigan, P., Edwards, S., and Ghandour, L.: 1995, ApJ, 452, 736 [HEG]

Hartmann, L., Hewett, R., and Calvet, N. 1994, ApJ, 426, 669

Herbst, W. and Wittenmyer, R.: 1997 B.A.A.S. 28, 1338

Johns, C. M., and Basri, G. 1995a, ApJ, 449, 341

Johns, C. M., and Basri, G. 1995b, AJ 109, 2800

Johns-Krull, C.M. and Basri, G. 1997, ApJ, 474,433

Kenyon,S., Yi, I. and Hartmann, L. 1996, 462, 439

Königl, A.: 1991, ApJ, 370, L39

Lada, C. J., and Wilking, B. A.: 1984, ApJ, 287, 610

Li, J. Wickramasinghe, D. and Ruediger,G.: 1996 ApJ, 469, 765

Martin S.C.: 1996, ApJ, 473, 1051

Martin S.C.: 1997, ApJ, 478, 33

Montmerle, T., Feigelson, E., Bouvier, J., and André, P. 1993 in *Protostars and Planets, III* ed. E.H. Levy and M.S. Matthews (University of Arizona Press), p. 689

Meyer, M., Calvet, N., and Hillenbrand, L.: 1997 AJ, in press

Najita, J., and Shu, F. H. 1994, ApJ, 429, 808

Najita, J., Carr, J.S., and Tokunaga, A.T. 1996, ApJ, 456, 292

Ostriker, E.C. and Shu, F.H.: 1995, ApJ, 447,813

Paatz, G., Camenzind, M.: 1996, A&A, 308. 77

Petrov, P.P., Gullbring, E., Ilyn,I., Gahm, G., Tuominen, I., Hackman, T. and Loden, K.: 1996, A&A, 314, 821

Popham, R.: 1996, ApJ., 467, 749

Shu, F.H., Najita, J., Ostriker, E., Shang, H.: 1995 ApJ 455, 155

Shu, F.H., Najita, J., Ostriker, E., Wilken, F., Ruden, S., and Lizano, S.: 1994 ApJ, 429,781

Strom, S.E., Edwards, S. and Skrutskie, M.F.: 1993, in *Protostars and Planets III*, ed. E.H. Levy and M.S. Matthews (University of Arizona Press)