RevMexAA (Serie de Conferencias), **1**, 285-291 (1995)

OBSERVATIONAL CONSTRAINTS ON DISK WINDS

Lee Hartmann
Center for Astrophysics, 60 Garden St., MS-15, Cambridge, MA 01238, USA

RESUMEN

Las únicas evidencias directas sobre la aceleración de un viento desde la superficie de un disco de acrecimiento de la presecuencia principal las proveen las observaciones espectroscópicas ópticas de los objetos FU Ori. Los ritmos de pérdida de masa de esos objetos se estiman en ≤ 0.1 del ritmo de acrecimiento de masa a través de los discos. Las observaciones implican que los objetos FU Ori tienen una gran eficiencia para convertir la energía que se libera en el acrecimiento en vientos o chorros. Sin embargo, las restricciones impuestas por las observaciones van en contra de la idea de que todo el momento angular del disco de acrecimiento sea transferido al viento, dado que ésto requeriría que la mayoría de la energía de acrecimiento fuera al viento en lugar de que emerja como radiación. Debido a que no hay evidencia de que la magnetosfera de la estrella central trunque los discos de acrecimiento rápido de los objetos FU Ori, los vientos de esos objetos indican que las magnetosferas estelares no son una componente esencial en la eyección rápida de masa protoestelar.

ABSTRACT

High-resolution optical spectroscopic observations of FU Ori provide the only direct evidence for acceleration of a wind from the surface of a pre-main sequence accretion disk. Estimated mass loss rates from FU Ori objects are ≤ 0.1 of the mass accretion rates through the disks. The observations imply that FU Ori objects have a very high efficiency in converting the energy released by accretion into winds or jets. However, the observational constraints are not consistent with the idea that all of the angular momentum of the accreting disk is transferred to the wind, because this would require most of the accretion energy to go into the wind, rather than emerge as radiation losses. Because there is no evidence that the magnetosphere of the central star effectively truncates the rapidly-accreting disks of FU Ori objects, FU Ori winds indicate that stellar magnetospheres are not an essential component of rapid protostellar mass ejection.

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

1. INTRODUCTION

The powerful bipolar outflows of early stellar evolution are thought to be magnetically accelerated from the surfaces of circumstellar accretion disks (see Königl & Ruden 1993 for an overview). The theoretical arguments supporting this mechanism are summarized in the articles by Königl (1995) and Najita (1995) in these Proceedings. In this paper I will discuss the most direct observational evidence for disk winds. Specifically, I will outline the spectroscopic evidence that the wind of FU Ori arises directly from the surface of the rapidly-accreting pre-main sequence disk in that system (see Kenyon's 1995 article for a discussion of FU Ori systems).

The observations of FU Ori are particularly important, because to my knowledge this is the only pre-main sequence object, and possibly the only astrophysical object, for which we can clearly demonstrate that the wind comes from a finite region of an accretion disk. Moreover, the studies of FU Ori systems place interesting constraints on theories of accretion disk winds. There are currently two extreme versions of disk wind theory. One, initially proposed by Pudritz & Norman (1983) and advanced by Königl and collaborators (Königl 1989; Wardle & Königl 1993; Safier 1993a,b) supposes that the wind, which is magnetically coupled to the disk, extends over a wide range in radii and carries away most of the angular momentum needed to allow accretion (e.g., Blandford & Payne 1982). The other extreme version of disk winds is that of Shu and collaborators (Shu et al. 1994a,b; Najita & Shu 1994), in which the disk wind arises only over a narrow region at the inner edge of the disk, where the magnetosphere of the T Tauri star truncates the disk. The FU Ori observations do not support either extreme version of the disk wind theory, but suggest instead an intermediate case, in which the wind is emitted from a modest area of the inner disk, and carries away a modest fraction of the total angular momentum of the accreting material.

Why do these details of protostellar disk winds matter? The two extreme models of disk winds differ mostly because they make vastly different assumptions about the strength and geometry of disk magnetic fields. Observational constraints can help us infer something about disk fields, and lead to a better understanding of how disk accretion energy can be efficiently transferred into jet energy. More generally, the geometry of disk winds plays a crucial role in permitting accretion and ejection to occur simultaneously. As Luis Rodriguez has said, we have become comfortable with the idea that infall and outflow are not direct antagonists; but I think this idea implicitly assumes that outflows really don't come from the outer disk. Outer disk winds will either (a) drive off the infalling material building up the disk in the first place or (b) be trapped by the infalling envelope. On the other hand, collimated inner disk jets/winds can easily escape out polar regions at the same time the outer disk can receive the bulk of the infalling matter. Here I shall argue that there is no strong evidence for outer disk winds, and suggest some further observational tests which could be used to place firmer constraints on such winds.

2. EMPIRICAL CONSTRAINTS ON FU ORI WINDS

The strong winds of FU Oris demonstrate a strong correlation between mass loss rate and disk accretion rate. FU Ori has an estimated wind mass loss rate of $\dot{M}_w \sim 10^{-5} M_\odot\, yr^{-1}$ (Croswell et al. 1987; Calvet et al. 1993), while the accretion rate through the disk is about an order of magnitude bigger, $\dot{M}_{acc} \sim 10^{-4} M_\odot\, yr^{-1}$. For comparison, the corresponding numbers for T Tauri stars are $\dot{M}_w \lesssim 10^{-8} M_\odot\, yr^{-1}$ (Edwards et al. 1993; Hartigan et al. 1995) and $\dot{M}_{acc} \sim 10^{-7} M_\odot\, yr^{-1}$ (Bertout et al. 1988; Hartigan et al. 1991). Since most of the FU Ori system luminosity is produced in the disk, and the kinetic energy luminosity of the wind is much larger than that of the presumed central T Tauri star (see below), it is evident that the wind is drawing on the energy released by disk accretion.

Because FU Ori objects have such strong winds, they exhibit spectroscopic signatures of mass loss that are not observable in T Tauri winds. In particular, Calvet et al. (1993) showed that the wind of FU Ori itself is so strong that it can be detected in many photospheric absorption lines, which exhibit net blueshifts in absorption. One can take advantage of the numerous spectral lines available for analysis to probe the wind as it emerges from the disk.

The basic idea is as follows. First, consider weak absorption lines formed near the disk photosphere. This material is basically in Keplerian rotation, and so the line profile will be split or "doubled" by the motion of the disk. The resulting absorption line profile will look something like the upper profile (dotted line) in the upper panel of Figure 1. Next, consider a line with a larger absorption strength. This line will be formed further up in the disk atmosphere, at greater heights above the disk midplane. Because the higher levels of the disk atmosphere are cooler, the line profile will be deeper, i.e. have a smaller residual intensity, just as if this were a stellar atmosphere. But at this higher atmospheric level, the gas density is lower; by conservation of mass for a (roughly) steady wind, the expansion velocity will be larger, and so the line profile will exhibit a blueshift. If the velocity shift due to expansion is small compared with the rotational velocity, the combination of both motions will result in a profile that is dominated by rotation. However, as one proceeds to consider stronger and stronger lines, eventually the level of line formation in the disk atmosphere is sufficiently high that the blueshift becomes important; so one expects to observe an increasing line velocity shift as the line profile becomes deeper.

This effect is shown by the sequence of line profiles in the upper panel of Figure 1. In these calculations the disk atmosphere is modelled as a series of disk annuli with different radii. The line profile for each annulus is calculated by assuming a locally plane-parallel atmosphere in gray gray vertical radiative equilibrium, with the boundary condition of the constant radiative flux generated by accretion below the photosphere at the appropriate radius. Profiles have been calculated for a series of Fe I lines of varying oscillator strength assuming LTE, adopting a linear acceleration of the expanding disk atmosphere combined with Keplerian rotation (see Calvet et al. 1993 for details). The sequence of profiles demonstrate quantitatively the profile evolution described qualitatively in the previous paragraph; atomic spectral lines of progressively greater strength compose a sequence of line profiles, with increasing line depth accompanied by an increasing blueshift of the absorption.

One simple way of characterizing this evolution of line profiles with increasing line strength is to consider the positions of the two absorption dips in the line profiles, marked in the upper panel of Figure 1 by the open circles for the redshifted component and filled circles for the blueshifted component. As the line strength increases, the line becomes deeper and so the two absorption dips appear at lower residual intensities; the line becomes more blueshifted, and the two dips move together. Eventually, for lines strong enough that they are formed at a high enough atmospheric level that the expansion velocity dominates the rotation, the two dips merge into one blueshifted feature.

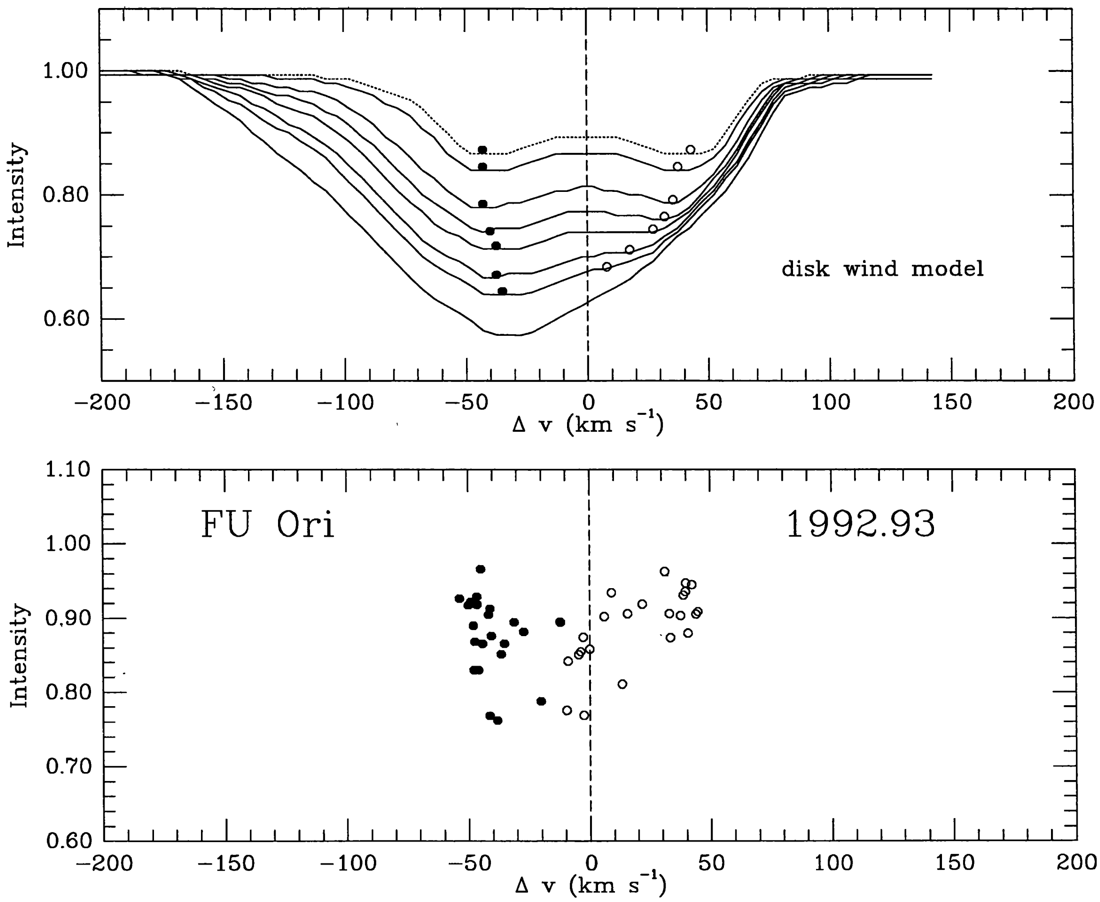

Fig. 1.— Upper panel: Prediction of the evolution of line profiles for a Keplerian disk with wind expansion (see text). Weak lines will be dominated by disk rotation, and so will show a doubled structure centered on the system velocity (dotted curve). Stronger absorption lines will exhibit a blueshift due to the expansion of the disk atmosphere (solid lines). The positions of the two absorption dips (open and filled circles) move together and appear at more negative velocities as the lines become deeper. Lower panel: measurements of the positions of the absorption dips of the photospheric lines in FU Ori. The filled and open circles mark the positions of the blueshifted and redshifted absorption dips, respectively, corresponding to the circles in the upper panel. The data show a clear trend for the line profile absorption dips to move blueward and to move together as the line strength increases (see text). From Hartmann & Calvet (1995).

This prediction for the positions of the blueshifted and redshifted absorption components can be observed in high-resolution optical spectra of photospheric lines in FU Ori. The bottom panel of Figure 1 (Hartmann & Calvet 1995) shows measurements of the positions of absorption dips of different lines. The data are somewhat noisy because of the problem of line blending at rapid rotation in FU Ori's spectrum, but the absorption dip positions show a clear trend like that predicted by the model. The tendency of the absorption components to move to greater blueshifts and to move together as line strength increases had first been demonstrated by Petrov & Herbig (1992) in an independent data set; we were able to confirm the Petrov & Herbig results.

By analyzing specific metal lines with a detailed disk atmosphere model, Calvet et al. (1993) were able to estimate a mass loss rate of $\sim 10^{-5} M_\odot\, yr^{-1}$ for FU Ori, similar to the crude estimate of Croswell et al. (1987) based on simultaneous analysis of the Hα and Na I resonance lines. Taking a typical terminal velocity, estimated from the strong Balmer and Na line profiles to be $\sim 300 km\, s^{-1}$, this implies a luminosity of the wind

$$L_{wind} = \frac{1}{2}\dot{M}_w v_\infty^2 \sim 75 L_\odot \,. \qquad (1)$$

When one considers that the present day accretion luminosity of FU Ori is $\sim 400 L_\odot$, one sees that a remarkably large fraction of the accretion energy is being diverted into the wind.

These results motivated Nuria Calvet and I (Hartmann & Calvet 1995) to investigate the line profiles of other FU Ori objects. Z CMa, V1515 Cyg, and V1057 Cyg all have prominent, extended blueshifted wind absorption in the Balmer series lines as well as in th strong Na I resonance lines. Blue-shifted wind absorption is also apparent in several strong Fe II lines (e.g., Welty et al. 1992). However, unlike FU Ori, the other objects do not show measurable velocity shifts in the weaker "photospheric" lines. This is demonstrated in Figure 2, where we show the measured velocities of the absorption dips for all four FU Ori objects measured at high resolution in the optical spectral region. Z CMa shows no evidence for the shifts seen in FU Ori; the two absorption dips of the line profiles resulting from disk rotation show no blueshift with increasing line strength. The instrumental resolution was not sufficient to show the two absorption dips independently in V1057 Cyg and V1515 Cyg, and so we just measured the line centroids. As for Z CMa, no evidence for a wind shift is observed.

We (Hartmann & Calvet 1995) extended the simple wind models originally developed for FU Ori to analyze the results for the other FU Ori objects. We found that the absence of blueshifts in Z CMa could be understood with the same or possibly slightly smaller mass loss rate as in FU Ori, because the larger projected rotational velocity of Z CMa tends to "hide" the wind blueshift. (The line profile can be understood as approximately the convolution of blueshifted wind absorption with the line broadening due to rotation; when the rotation is large in comparison with the wind blueshift, the rotational doubling dominates the resultant line profile.) On the other hand, this explanation cannot apply to the other two FU Ori objects, which have much smaller projected rotational broadening. In the case of V1515 Cyg, the mass loss rate is estimated to be about an order of magnitude smaller, based on both the absence of blueshifted photospheric lines and modelling of the Fe II 5018 Å P Cygni profile.

These results are summarized in Table 1. V1057 Cyg was not modelled in detail because it has a significantly different spectral type than the other objects, and so required a separate analysis not yet completed; but it is likely to have a mass loss rate similar to that of V1515 Cyg.

TABLE 1
FU Ori Wind Results

Object	$\dot{M}_w$ ($M_\odot\, yr^{-1}$)	v_∞ ($km\, s^{-1}$)	L_{rad} ($L_\odot$)	KE(wind)/L_{rad}
FU Ori	10^{-5}	300	400	0.2
Z CMa	3×10^{-6} - 10^{-5}	800	600	0.3 - 0.9
V1515 Cyg	$\sim 10^{-6}$	200	250	0.013

3. MASS AND ANGULAR MOMENTUM LOSS

Although the ratios of kinetic energy wind flux to radiative luminosity given in the last column of Table 1 are not much better than order of magnitude estimates, they still have significance for disk wind theory. Our results imply that FU Ori disks are efficient in converting accretion energy into wind kinetic energy. However, they do not support the extreme version of wind theory in which the wind takes away all of the angular momentum needed for accretion. The reason for this is simple; MHD winds which carry away all of the angular

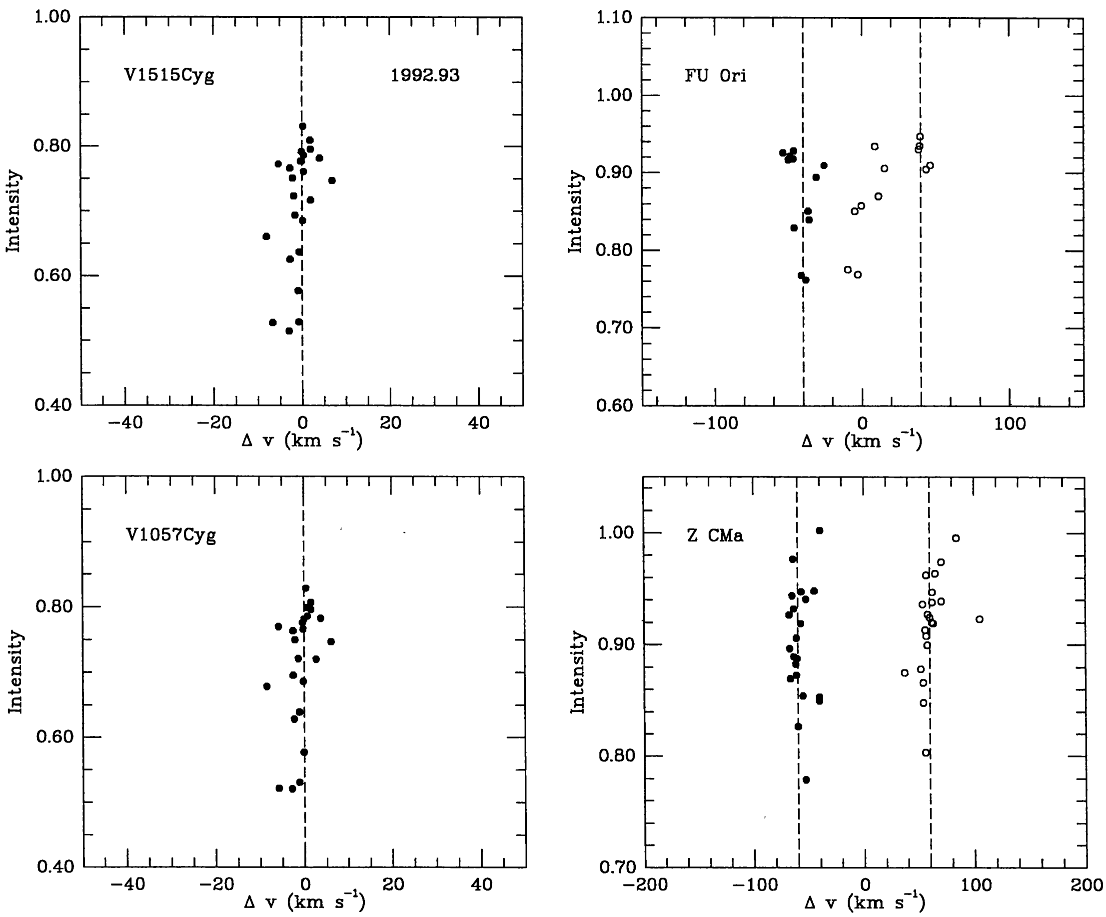

Fig. 2.— Absorption line shifts of FU Ori objects. The upper right panel repeats the FU Ori data displayed in the lower panel of Figure 1. The lower right panel shows corresponding data for Z CMa, which (unlike FU Ori) does not show velocity shifts in the positions of the absorption dips. The spectral resolution was not sufficient to clearly distinguish the absorption dips of the other two FU Ori objects (see text), and so only the overall line shift is plotted as a function of the depth of the line. From Hartmann & Calvet (1995).

momentum of accretion take away nearly all of the accretion energy as well (e.g., Königl 1989). This leaves very little energy behind to be *radiated* by the disk (the third column in Table 1). It must be admitted that our mass loss rates are uncertain; in particular, it is difficult to constrain the velocity gradient of the wind precisely, which is needed to convert an absorption line column density into an absolute wind density at a given velocity. However, I don't think that our general result, $KE(wind)/L_{rad} \lesssim 10^{-1}$, can actually be consistent with the ratio $KE(wind)/L_{rad} >> 1$ as required by the extreme wind theory.

In addition, the extreme wind theory implies that the true mass accretion rates of FU Ori objects are much larger than currently estimated from radiative losses. This would imply $\dot{M}_{acc} \gtrsim 10^{-3} M_{\odot}\, yr^{-1}$, with accretion of $\gtrsim 0.1 M_{\odot}$ during a single FU Ori event. Because event statistics suggest at least 10^1 outbursts per FU Ori object (Hartmann et al. 1993), this is an uncomfortably large value for the accreted mass. It seems much more consistent with present limits to assume that most of the accretion energy in an FU Ori event is radiated away - which in turn implies that the wind does not carry away most of the accretion energy, independent of any estimates of mass loss rates.

The simplest explanation of the FU Ori observations is that the wind is not the major mechanism in transferring angular momentum out of the disk. Since one of the strongest motivations for the very extended disk wind was to solve the angular momentum transport problem, there is really no strong motivation for having an extended disk wind.

Pelletier & Pudritz (1992) have considered models in which the disk wind is not self-similar, but is more concentrated to the inner disk. It would be interesting to apply some variant of these theoretical wind models to FU Ori objects.

4. DUSTY WINDS?

Königl (1995) suggests that an extended disk wind would be dusty, and that the infrared radiation from this dusty wind could explain some of the excess infrared emission observed in some T Tauri stars. There are two difficulties I see with accepting this idea;

(1) FU Ori objects have very strong winds, with mass loss rates two to three orders of magnitude larger than T Tauri stars, and yet there is little evidence for a high-extinction, dusty wind. In particular, in FU Ori itself there is no evidence for a dusty envelope with any extinction greater than $A_V \sim 2$ (Hartmann et al. 1993). It might be that the massive wind only arises from inner disk regions, where the disk is so hot that dust is evaporated; but if this is true, then there cannot be a substantial outer disk wind in any event. Moreover, it should be noted that there is evidence for a brief episode of dust formation in the wind of V1515 Cyg (Kenyon et al. 1991).

(2) If the dusty wind is flowing out, than one should be able to observe a redshifted spectrum of the central star in scattered light. Although several T Tauri stars are known to be seen only in light scattered from a surrounding dusty envelope, based on their high system polarization (see Whitney's 1995 discussion in these Proceedings), there is no evidence for large velocity shifts from moving dust- the radial velocities measured for these objects are close to the local molecular cloud velocities. For example, in the case of HL Tau, a young T Tauri star that is observed optically entirely from light scattered off its surrounding dusty nebula, our measurements (Hartmann & Calvet 1995, in preparation) and those of Grasdalen et al. (1989) show no evidence for any measurable velocity shift (relative to the molecular cloud) greater than about 3 $\mathrm{km\,s^{-1}}$. Additional efforts can and should be made to detect or limit velocity shifts from moving dust; the results of such observational programs will place the firmest constraints on expanding dusty winds.

5. X-CELERATOR MODEL AND FU ORI OBJECTS

Shu (1994a,b) and Najita & Shu (1994) have proposed that the winds of T Tauri stars originate at the inner edge of circumstellar disks truncated by the stellar magnetosphere (see also Najita 1995). This model does not seem to apply to FU Ori objects; we have no observational evidence for magnetospheres truncating FU Ori disks. Moreover, as pointed out by Shu et al. (1994a), at the high accretion rates of FU Ori disks one would expect the stellar magnetosphere to be pretty effectively crushed down to the stellar surface by the accretion disk. In this case, FU Ori winds show that magnetospheric disk truncation is not necessary to produce a powerful outflow, unlike the implication of the Shu et al. (1994a) discussion. The disk of FU Ori disk must contain its own magnetic field to accelerate the cold outflow from the disk surface. Since FU Ori winds are so strong, and the evidence for time-dependent outflows is compelling (Reipurth 1989a,b), it may be that we should concentrate on understanding outflows in rapid accretion states, such as FU Oris, rather than developing a theory which is most suitable for low-accretion rate T Tauri stars, which have the weakest outflows.

This research was supported in part by NSF grant INT-9203015 and by NASA grant NAGW 2306.

REFERENCES

Bertout, C., Basri, G., & Bouvier, J. 1988, ApJ, 330, 350
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Calvet, N., Hartmann, L., & Kenyon, S. J. 1993, ApJ, 402, 623
Croswell, K., Hartmann, L., & Avrett, E. H. 1987, ApJ, 312, 227
Edwards, S., Ray, T., & Mundt, R. 1993, in Protostars and Planets III, ed. E. H. Levy & J. Lunine (Tucson: University of Arizona Press), 567
Grasdalen, G. L., Sloan, G., Stout, M., Strom, S. E., & Welty, A. D. 1989, ApJ, 339, L37
Hartigan, P., Kenyon, S. J., Hartmann, L., Strom, S. E., Edwards, S., Welty, A. D., & Stauffer, J. 1991, ApJ, 382, 617
Hartigan, P., Edwards, S., & Ghandour, L. 1995, ApJ, in press
Hartmann, L., & Calvet, N. 1995, AJ, in press

Hartmann, L, Kenyon, S. J., & Hartigan, P. 1993, in Protostars and Planets III, ed. E. H. Levy & J. Lunine, (Tucson: University of Arizona Press), 497

Kenyon, S. J. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 237

Kenyon, S. J., Hartmann, L., & Kolotilov, E. A. 1991, PASP, 103, 1069

Königl, A. 1989, ApJ, 342, 208

Königl, A. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 275

Königl, A., & Ruden, S.P. 1993, in Protostars and Planets III, ed. E. H. Levy & J. Lunine (Tucson: University of Arizona Press), 641

Najita, J. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 293

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

Pelletier, G., & Pudritz, R. E. 1992, ApJ, 394, 117

Petrov, P. P., & Herbig, G. H. 1992, ApJ, 392, 209

Pudritz, R. E., & Norman, C. A. 1983, ApJ, 274, 677

Reipurth, B. 1989a, Nature, 340, 42

Reipurth, B. 1989b, in ESO Workshop on Low-Mass Star Formation and Pre-Main Sequence Objects, ed. B. Reipurth (ESO:Garching), 247

Safier, P. 1993a, ApJ, 408, 115

Safier, P. 1993b, ApJ, 408, 148

Shu, F. H., Lizano, S., Ruden, S. P., & Najita, J. 1988, ApJ, 328, L19

Shu, F. H., Najita, J., Ostriker, E., Wilkin, F., Ruden, S. P., & Lizano, S. 1994a, ApJ, 429, 781

Shu, F. H., Najita, J., Ruden, S. P., & Lizano, S. 1994b, ApJ, 429, 797

Wardle, M., & Königl, A. 1993, ApJ, 410, 218

Welty, A. D., Strom, S. E., Edwards, S., Kenyon, S. J., & Hartmann, L. W. 1992, ApJ, 397, 260

Whitney, B. A. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 201