YSO Jets and Molecular Outflows: Tracing the History of Star Formation

Adam Frank

Abstract.

Collimated outflows from Young Stellar Objects (YSOs) can be seen as tracers of the accretion powered systems which drive them. In this paper I review some theoretical and observational aspects of YSO outflows through the prism of questions relating to the protostellar source. The issue I address is: can collimated outflows be used as “fossils” allowing the history of protostellar evolution to be recovered? Answering this question relies on accurately identifying where theoretical tools and observational diagnostics converge to provide unique solutions of the protostellar physics. I discuss potential links between outflow and source including the time and direction variability of jets, the jet/molecular outflow connection, and the effect of magnetic fields. I also discuss models of the jet/outflow collimation mechanism.

INTRODUCTION

Collimated outflows from Young Stellar Objects take the form of both narrow high speed jets and bipolar molecular outflows [26]. The last two decades has witnessed rapid growth in our understanding of these systems as hydrodynamic/hydromagnetic phenomena. Emission line diagnostics have allowed conditions in the jets to be studied in considerable detail [16], [15] while numerical simulations have successfully cataloged the physics of jet propagation [20]. Recent HST images have revealed the morphology of HH jets in such detail as to strongly constrain all future theoretical models of YSO outflows (in what follows I will refer to collimated YSO flows in general as “outflows” and will specifically distinguish jets from molecular outflows when needed).

While the rapid progress of YSO collimated outflow studies is heartening for jet enthusiasts it also holds the promise of providing substantive answers to questions relating directly to the star formation process itself. With an abundance of high resolution spectral and imaging data the morphology, kinematics and microphysical state of the outflows can be mapped out in detail. On the theoretical side numerical models are now becoming sophisticated enough to include accurate inventories
of microphysical processes which produce emission. In this way fine grained comparison between outflow observations and models is becoming possible. Strong constraints on outflow models should allow researchers to look back to the source and discriminate between competing scenarios of accretion processes responsible for assembling the star. Such a synergy between theory and data will allow the details of accretion related processes to be recovered from collimated outflows the way biological evolution is read off the fossil record. The principal difficulty in this endeavor is to establish which questions to ask.

Using collimated outflows as fossil tracers of protostellar physics can succeed if researchers identify issues which provide a reasonably unique and unambiguous bridge between the large scale outflows \((L \leq 10^7 \text{AU})\) and accretion processes occurring on smaller scales \((L \leq 10^2 \text{AU})\), see Calvet, these proceedings). Only those characteristics of the jets imposed close to the star (or at the nozzle where collimation occurs) will be useful. It is important therefore to cleave between features in the outflows imposed by accretion related physics and those related to secondary mechanisms such as interactions with the intercloud/interstellar medium. For instance, characteristics which result from dynamical instabilities can only provide insights into accretion process when they can be linked to properties near the central object \([34],[29]\).

In what follows I attempt to identify some issues currently under study that might establish the needed bridge between outflows and the accreting protostar. This list is by no means complete and I apologize in advance for neglecting, due to lack of space, many important investigations contributing to what might be called “YSO outflow paleontology”.

**OBSERVATIONS: HH JET BEHAVIOR**

Fig 1 (taken from Reipurth et al. 97) shows HST images of three images of jets with HH objects: HH111, HH34, and HH46/47. These systems illustrate key features common to many HH object/jets \([27]\).

All three jets show spatial variability on a variety of scales. In particular, closely spaced chains of knots are visible in all three systems. Sequences of larger, more widely separated features showing distinct bow shock morphologies, also occur in all three jets. If the spatial variations result from time variations inherent to the jet source then the knots and bowshock chains give timescales of \(\Delta t_{\text{knot}} \approx 1 − 10 \text{ y} \) and \(\Delta t_{\text{bow}} \approx 100 − 1000 \text{ y} \) respectively \([24],[15]\). Much longer chains of HH objects have recently been discovered by Bally and collaborators (these proceedings). These “super-jets” can extend out to distances on the order of a few parsecs. Dynamical ages for the super-jet systems can be as large as \(t \approx 10^5 \text{ y} \), comparable to the time it takes to assemble the protostellar sources.

While HH111 and HH30 are remarkably straight, HH47 shows evidence of direction variability on different scales. Note in particular how the jet beam in HH47 appears to connect to the side of the bright bow shock. Both molecular outflows
and the super-jets show evidence for direction variability in the form of either precession (which produces point-symmetric S-shaped configurations) or random variations in the form of jet “wandering”.

Proper motion studies show the gas in these systems is traveling at $v_j \approx 300 \text{ km/s}$. Spectral line diagnostics indicating the level of excitation and ionization in the shocks yield speeds of order $v_s < 100 \text{ km/s}$ [16]. The disparity between these two speeds strengthens the case for very long jet lifetimes as they indicate the visible portions of the jet are propagating into invisible jet material ejected earlier.

The velocity and direction variability identified above may yield the strongest points of contact relating large scale outflows to processes at the source. In the next two sections I review theoretical models which attempt to establish an explicit link between jet propagation physics and variability at the source.

**JET VARIABILITY AND THE MOLECULAR OUTFLOW CONNECTION**

Numerical simulations have taken the study of YSO jets into maturity. Jets can be decomposed into 4 main dynamical elements: the beam of unshocked jet material; the jet shock which decelerates material in the jet beam; the bow shock which accelerates ambient material; the cocoon decelerated jet gas surrounding the beam; The pioneering work of Blondin, Fryxell & Konigl (1990) demonstrated the dramatic effect that collisionally excited radiative losses have on jet propagation dynamics. Their simulations showed that heavy ($\eta = \rho_j/\rho_a > 1$, $a =$ ambient, $j =$ jet) “radiative jets” differ substantially from “light” ($\eta < 1$) extra-galactic jets. In radiative jets the loss of pressure support in post-shock regions collapses the bow and jet shocks into a thin dense shell which quickly fragments. The pressure in the cocoon is also reduced. Thus, unlike light jets, the cocoon in a radiative jet does not drive pressure waves into the beam allowing it to remain relatively undisturbed.

Simulations which include velocity variability at the source have been explored by a number of authors, ([33], [9], [2]) including a recent, noteworthy investigation by Suttner et al. 1997. These studies demonstrate that periodic velocity pulses produce multiple “internal working surfaces” downstream in the beam as faster material catches up to, and shocks slower moving gas. These results argue that the widely separated multiple bow shocks observed in YSO jets can be attributed directly to temporal variations at the jet source. The situation is less clear for the narrowly spaced chains of knots. Recent studies of Kelvin-Helmholtz instabilities in YSO jets have shown that small scale periodic structures can be imposed in the jets via dynamics inherent to the beam itself ( [34] [30]). On the other hand simulations of magneto-centrifugal jet production [21] show short time-scale variations imposed in the beam due to processes inherent to the collimation process.

The connection between jets and Molecular Outflows remains one of the most important issues facing YSO studies [5]. Like the jets, bipolar molecular outflows
FIGURE 1. Combined Hα and [SII] emission maps of three HH jet systems from Reipurth et al. 1997.
are ubiquitous in protostellar environments and many YSOs exhibit both phenomena. After almost two decades of study it is still unclear if the jets and outflows are causally related or simply co-extensive. Competing models invoke either a “wide-angle wind” [31] or a jet [18] to drive the molecular outflows. Discriminating between these models has direct impact on issues relating to the physics of the protostar.

While some molecular outflows are quite narrow, many show poor collimation with rather wide lobes and low aspect ratios. Among other problems, jet driven models have difficulty explaining the variety of outflow shapes. This is an issue where variations in jet direction may have a direct bearing. The effect of variations in jet direction has been studied in precessing or wandering jet models. Raga Canto & Biro (1993) argued that changes in the jet direction would produce weak ”sideways shocks” propagating across the jet cross section which may be observable. Using 3-D simulations Cliffe, Frank & Jones (1996) confirmed this prediction and demonstrated that direction variability leads to significant deceleration of the leading sections of the jet. By including a calculation of microphysical processes Suttner et al. (1997) have shown that jets with precession and velocity variations imposed at the source produce kinematical patterns well matched with observations.

Both Cliffe, Frank & Jones (1996) and Suttner et al. (1997) have taken some steps in addressing the width of jet driven molecular outflow lobes. Based on earlier suggestions [18], these authors demonstrated that precessing jets will produce a wide global bow shock enveloping the entire “corkscrew” of the jet. If this global bow shock structure can be identified with molecular outflows it may allow jet driven models to recover both narrow and wide outflow lobes as the result simply depends on the precession or wandering angle. Velocity variations [23] in the beam have also been used as a means for widening jet driven outflows. In these models the bow shock is inflated via pressure from gas “squirted” out the sides of internal shocks.

**MAGNETIZED RADIATIVE JETS**

Hydrodynamic jets with and without radiative losses have been well-studied. Magnetized jets subject to collisionally excited radiative losses have not, as yet, received extensive scrutiny. Given the consensus that MHD processes are responsible for producing astrophysical jets this represents a rather large gap in our understanding of YSO outflows systems and constrains our ability to make connections with protostellar physics. If the collimation process at the source is MHD dominated then magnetic fields will remain embedded in the jets as they propagate. In particular both disk-wind ([21], see references therein) and X-wind (Ostriker, these proceedings) models of jet collimation produce jets with strong toroidal ($B = B_\phi$) fields. The strength of the jet fields can be seen in the relevant Mach numbers. While sonic Mach numbers of MHD collimated jets may be high ($M_s > 10$) the fast mode Mach numbers are quite low ($M_f \approx 3$, [8]).
Direct observation of magnetic fields in protostellar jets would help clarify issues surrounding jet origins. Unfortunately such measurements have generally proven to be difficult to obtain [25]. A promising alternative is look for less direct tracers of strong fields in YSO jets. If jets are produced via MHD processes, dynamically significant magnetic stresses should affect the beam and jet head as they interact with the environment. Thus the propagation characteristics of protostellar jets may hold important clues to their origins.

Cerqueira et al. (1997) and Frank et al. (1997) have recently reported the first multi-dimensional simulations of radiative MHD jets. Both studies demonstrate that propagation characteristics of jets with strong toroidal fields differ significantly from their pure hydrodynamic cousins. This is illustrated in Figure 2 (from Frank et al. 1997) which compares the results of a weak field and a strong field radiative jet simulation. Comparison of the two cases demonstrates the effect of strong toroidal fields and cooling. The weak field jet exhibits a dense shell and a relatively undisturbed jet beam. In the strong field case however “hoop” stresses associated with the radially directed magnetic tension force inhibit sideways motion of shocked jet gas. Material that would have spilled into the cocoon is forced into the region between the jet and bow shock, forming a “nose-cone” of magnetically dominated low $\beta$ gas ($\beta = P_g/P_B = 8\pi P_g/B^2$) [20]. Hoop stresses also collapse the beam near the nozzle, producing strong internal shocks due to magnetic pinches.

Fig 2. shows that the weak and strong field radiative jets look dramatically different from each other in terms of the morphology of the jet head and beam. In the weak field case there are no shocks in the beam. The strong field case shows multiple shock reflections. The head of the weak field jet is quite “blunt” compared with the strongly tapered strong field jet. The kinematics of the two jets also differ. The average propagation speed for the head of the strong field jet is $\approx 40\%$ higher than the weak field case, even though both simulations have the same jet/ambient density ratio, $\eta$. The combination of higher shock speeds and strong pinch forces in the radiative strong field jet produces a higher compression ratio in the head of strong field jet. If these results are born out in more detailed studies, particularly those in 3-D, then indirect diagnostics of the presence of dynamically strong fields in jets should exist.

**JET COLLIMATION**

Of course the best way to link outflows with their protostellar sources is to understand exactly how outflows are created. Obscuration and resolution issues make observations of the inner collimation regions difficult but progress is being made. A number of studies have provided strong evidence that jet collimation must occur on observational scales of order $R \leq 10\,\text{AU}$ ( [24]).

The current consensus in the astrophysical community holds that YSO jets are launched and collimated by MHD processes. The most popular models rely on magneto-centrifugal forces in either an accretion disk (“Disk-winds”) or at the disk-
star boundary ("X-winds"). These studies have been quite successful in articulating the physical properties of MHD collimation processes. Indeed numerical simulations [21] have recently demonstrated the ability of disk-wind models to produce both steady and time dependent jets (Fig 3). Models which rely on the interaction of a dipole stellar field tied to an accretion disk have also shown promise in both analytic and numerical studies ([13] and references therein).

In spite of this success many questions remain. The existence of variety of working models leads to a basic uncertainty as to which mechanism YSOs choose if MHD is the dominant launching and collimation process. There are also questions as to the effectiveness of collimation in MHD models. As Shu et al. 1995 point out MHD collimation can be a slow process occurring logarithmically with height above the disk. A different set of numerical simulations [28] found that while the magneto-centrifugal process was effective at launching a wind, it did not produce strong collimation of the wind into a jet.

Along with these issues, recent numerical studies have shown that pure hydrodynamic collimation can be surprisingly effective at producing jets. Frank & Mellema (1996) and Mellema & Frank (1997) have demonstrated that isotropic or wide angle YSO winds interacting with toroidal density environments produce oblique inward facing wind-shocks. These shocks can be effective at redirecting the wind material into a jet (see Fig 3). If the wind from the central source is varying this "shock focusing" mechanism can, in principle, collimate jets on the observed physical scales. Similar mechanisms have been shown to work to in other jet-producing contexts, particularly Planetary Nebulae. [11] [4].

The variety of models currently available to produce YSO jets begs the question of which observational diagnostics are needed to distinguish the processes actually producing the jets. Further progress will come as the collimation models mature and are capable of predicting observational consequences (ie from $B$ fields or shocks) in observable regions of the flow. Thus critical observations concerning the formation of the jets will, once again, have to come from downstream of the collimation regions, i.e. from the jets themselves.

I SUMMARY

The issues cited in this paper are associated with outflows. How do these issues specifically relate to questions inherent to the physics of accretion? The time variability of jets relates to the time-dependence of accretion, the FU Ori outbursts being a notable example. The direction variability of jets relates to the global dynamics and stability of accretion disks. Livio & Pringle 1997, for example, have shown that radiation induced warping of disks may lead to precession in magneto-centrifugal jets. The presence and structure of magnetic forces in jets relates to the existence and form of large scale fields in the disks. If nose-cones do not occur in real YSO jets then perhaps mechanisms which rely on strong toroidal fields are excluded.
Thus YSO jets and outflows offer a unique opportunity for the study of accretion powered systems. Protostellar outflows can be observed with exquisite detail in a variety of wavelengths including diagnostic spectral lines. The quality of the data combined with the long lookback time inherent to the outflows offers the possibility that a large fraction of individual protostar’s history might be recovered if we learn were and how to look. We are a long way from this now but the prospect of having such capabilities is very exciting.

REFERENCES

1. Biro, S., Raga, A. C., & Cantó, J. 1993, MNRAS, 260, 625
2. Biro, S., Raga, A., 1994, ApJ, 434, 221
3. Blondin, J.M., Fryxell, B.A., & Königl, A., 1990, ApJ 360, 370
4. Borkowski, K., Blondin, J., Harrington, J., 1997, ApJ, 482L, 97
5. Cabrit, S., Raga, A., & Gueth, F., 1997, in Herbig-Haro Flows and the Birth of Low Mass Stars, in IAU Symposium no. 182, eds B. Reipurth & C Bertout, (Kluwer, Dortdrecht)
6. Cerqueria, A., Gouveia Dal Pino, E., & Herant, M., 1997, ApJ, 489L, 185
7. Cliffe, A., Frank, A., & Jones, T.W., 1996, MNRAS, 282, 1114
8. Camenzind, M., 1997 in Herbig-Haro Flows and the Birth of Low Mass Stars, in IAU Symposium no. 182, eds B. Reipurth & C Bertout, (Kluwer, Dortdrecht)
9. De Gouveia Dal Pino, E. M., Benz, W., 1994, ApJ, 435, 261
10. Frank, A., & Mellema, G., 1996, ApJ 472, 684
11. Frank, A, Balick, B, Livio, M., 1996, ApJ, 471L, 53
12. Frank, A., Jones, T. W., Ryu, D., & Noriega-Crespo, A., 1997 ApJ, in press
13. Goodson, A, Winglee, R., Boehm, K., 1997, ApJ, 489, 199
14. Gueth, F., Guilloteau, S., Bachiller, R. 1996, A&A, 307, 891
15. Heathcote, S., Morse, J., Hartigan, P., Reipurth, B., Schwartz, R., Bally, J., & Stone, J., AJ, 112, 1141
16. Hartigan, P, Morse, J, Raymond, J, 1995, ApJ, 444, 943
17. Livio, M, Pringle, J., 1997, ApJ, 486, 835
18. Masson, C, Chernin, L., 1993, ApJ, 414, 230
19. Mellema, G., & Frank 1997, MNRAS, in press
20. Norman, M.L. 1993, in “Astrophysical Jets”, eds. D. Burgarella, M. Livio, & C. O’Dea, Cambridge University Press, 210.
21. Oyued R., & Pudritz, R. E. 1997, ApJ, 482, 712
22. Raga, A. C., Cantó, J., & Biro, S. 1993, MNRAS, 260, 163
23. Raga, A.C., & Cabrit, S., 1993, A&A, 278, 26
24. Ray, T, Mundt, R., Dyson, J., Falle, S., & Raga, A. 1996, ApJ, 468L
25. Ray, T., Muxlow, T., Axon, D., Brown, A., Corcoran, D., Dyson, J., & Mundt, R. 1997, Nature, 385,415
26. Reipurth, B., Hartigan, P., Heathcote, S., Morse, J., & Bally, J., 1997, AJ, 114, 757
27. Reipurth, B., 1997, in Herbig-Haro Flows and the Birth of Low Mass Stars, in IAU Symposium no. 182, eds B. Reipurth & C Bertout, (Kluwer, Dortdrecht)
28. Romanova, M., Ustyugova, G., Koldoba, A., Chechetkin, V., & Lovelace, R., 1997, ApJ, 482,70
29. Rossi, P., Bodo, G., Massaglia, S., Ferrari, A., 1997, A&A, 321, 672
30. Rubini, F., 1997, in Herbig-Haro Flows and the Birth of Low Mass Stars, in IAU Symposium no. 182, eds B. Reipurth & C Bertout, (Kluwer, Dortrecht)
31. Shu, F, Ruden, S, Lada, C, Lizano, S. 1991, ApJ, 370L
32. Shu, F., Najita, J., Ostriker, E., & Shang S., 1995, ApJ, 495, L155
33. Stone, J.M., & Norman, M.L. 1993, ApJ, 413, 210
34. Stone, J., Xu, J., Hardee, P., 1997, ApJ, 483, 136
35. Suttner, G. Smith, M. D. Yorke, H. W.& Zinnecker, H.,1997, A&A, 318, 595
FIGURE 2. Comparison of two YSO Jet simulations from Frank et al 1997. Top: Grey-scale density map from a weak field radiative model (at $t = 1,971 \, \text{y}$). Bottom: Grey-scale density map from a strong field radiative model (at $t = 1,460 \, \text{y}$). Both jets have sonic mach numbers $\approx 10$. The strong field jet has a fast mode mach number $\approx 5$. Note that narrow bow shock and strong internal beam shocks in the strong field case.
FIGURE 3. Comparison of MHD and Hydrodynamic Jet collimation models. Left panel: greyscale representation of density from a MHD disk wind simulation (Ouyed and Pudritz 1997). Right: greyscale representation of density from a hydrodynamic collimation model (Mellema & Frank 1997). In the hydrodynamic model a spherical wind from the protostar interacts with a toroidal density distribution producing a supersonic jet.