RevMexAA (Serie de Conferencias), **36**, 179–185 (2009)

GETTING TO GRIPS WITH THE UNKNOWN: HOW IMPORTANT ARE MAGNETIC FIELDS IN OUTFLOWS FROM YOUNG STARS?

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RESUMEN

Los flujos estelares son una parte siempre presente en el proceso de formación estelar, y tal vez sean necesarios para que la acreción ocurra sobre una protoestrella o sobre una enana café joven. Mientras los flujos pueden tomar distintas formas, son más notables cuando se observan jets supersónicos altamente colimados que pueden extenderse por varios parsecs. La emisión de linea de estos jets puede ser usada para derivar casi todos los parámetros físicos básicos, como la densidad, temperatura, fracción de ionización, etc. En contraste, ha resultado difícil medir sus campos magnéticos. Hago un resumen de las evidencias observacionales directas e indirectas que indican que los campos magnéticos juegan un papel importante no sólo en el lanzamiento de los jets sino tambien en su colimación. En el futuro cercano, observaciones de radio de débiles emisiones no térmicas, con instrumentos como LOFAR y e-MERLIN, y estudios polarimétricos del componente de polvo de los jets, deberían ayudarnos a obtener estimaciones de la magnitud y de la estructura de sus campos magnéticos.

ABSTRACT

Outflows are a ubiquitous part of the star formation process and may even be necessary if accretion is to occur onto a protostar or young brown dwarf. While an outflow can take several forms, it is most strikingly seen as a highly collimated supersonic jet that can stretch for several parsecs. Line emission from these jets can be used to derive practically all of their basic physical parameters, such as density, temperature, ionisation fraction, etc. In contrast, their magnetic fields have proven very difficult to measure. Here I review what direct and indirect observational evidence we have that magnetic fields play an important role not only in launching jets but in their subsequent collimation. In the near future, radio observations of any weak non-thermal emission, with instruments such as LOFAR and e-MERLIN, and polarisation studies of the dust component in jets, should help us make estimates of the strength and structure of their B fields.

Key Words: H II regions — ISM: ets and outflows — stars: mass loss — stars: pre-main sequence

1. INTRODUCTION

Jets and outflows from young stars are not only spectacular signposts of star formation but also one of the most striking astrophysical phenomena. Their discovery was ushered in by the widespread use of CCDs in astronomy. Today our understanding of jets has increased enormously although there are many fundamental questions still to be answered, the most important of which is: how are they launched? If, as some people believe, the launching mechanism is universal, and operates in such diverse environments as active galactic nuclei (AGN), gamma-ray bursters (GRBs), cataclysmic variables (CVs), X-ray binaries as well as young stars and brown dwarfs, then determining what that mechanism is, is not only of relevance to star formation, but also much of modern astrophysics. A case can be made that, given the large amount of knowledge we have about jets from young stellar objects (YSOs), they represent our best chance of "decoding" what that mechanism is. While there is universal agreeement that it must involve magnetic fields, the precise details remain elusive.

Ironically, the strength and direction of magnetic fields in YSO jets remain their most poorly known parameters while almost all other quantities, density, temperature, ionisation fraction, etc., are readily determined, as we shall see. In this sense they are almost the polar opposites of AGN jets. As I will show however, we do have some clues, direct and indirect, as to the importance of magnetic fields in YSO jets. Before discussing these, however, I will begin with a review of some basic jet properties (§ 2), followed by a discussion of what we know, directly or indirectly, about their magnetic fields and future prospects for measuring them (§ 3). Finally some conclusions are made (§ 4).

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2. BASIC PROPERTIES OF YSO JETS

Although YSO jets per se were not discovered until a quarter of a century ago (Craine et al. 1981; Mundt & Fried 1983; Reipurth et al. 1986), their brightest components were known many years before (Herbig 1951; Haro 1952) and are referred to as Herbig-Haro (HH) objects. At the time these "nebulous patches" were found, it was not realised that they were part of an outflow, instead they were thought to be possible sites of star formation. This picture changed however, particularly with the use of spectroscopy. We now know the line emission spectrum of HH objects closely resembles that of their associated jets and it is through the combination of spectroscopy and multi-epoch imaging that we have learnt the most about YSO jet properties.

Typical velocities (as determined from spectroscopy and proper motion measurements) are around 200–300 km s^{-1}, in other words close to the gravitational escape velocity from the surface of the young star. Their temperatures, as derived from various line ratios, are around 10^4K, corresponding to a sound speed of approximately 10 km s^{-1}. It follows that they are highly supersonic with Mach numbers, M_{jet}, around 20–30. While the opening angles, θ_{jet}, of jets vary, these are typically only a few degrees, i.e. close to the ballistically expected value of $\theta_{jet} \approx 1/M_{jet}$ (Mundt et al. 1991; Ray et al. 2007). Note also that such high degrees of collimation are evident not only in ionized and neutral atomic species but in high velocity molecular emission (Codella et al. 2007) as well. Finally the dimensions of YSO jets may extend to several parsecs, i.e. comparable in some cases to their parent molecular cloud. It has even been suggested that their interaction with the cloud may provide it with turbulent support against gravitational collapse (see Frank et al. 2009).

Using their line emission, it is possible to derive typical shock velocities in YSO jets which are found to be considerably less than the corresponding jet velocity. It follows that the shocks are either oblique or due to velocity variations in the outflow close to the source (e.g. Raga et al. 1990). Their morphology, particularly at high spatial resolution with *HST*, suggests the latter is almost certainly the correct interpretation (Ray et al. 1996).

The emission we observe from HH objects and jets comes from post-shock cooling zones where, for example, the density is enhanced. To derive preshock values, and in particular to determine the ionization fraction, we need to either model the shock (e.g. Hartigan et al. 1994) or use an approximation

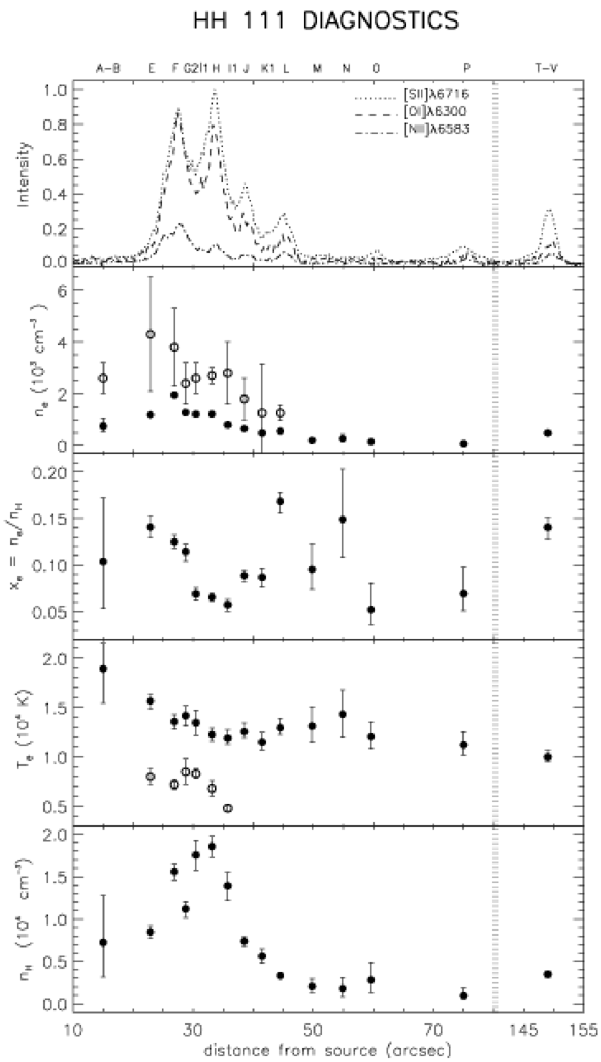

Fig. 1. Variation of parameters along the HH 111 jet. From top to bottom: intensity (for different optical lines), electron density, n_e, in units of 10^3 cm^{-3}, ionization fraction, x_e, temperature, T_e, in units of 10^4 K and total density, n_H, in units of 10^4 cm^{-3}. Open circles are values derived from infra-red [Fe II] lines, while the filled circles are parameters inferred from the optical S^+, N^+ and neutral O lines using the BE technique (see text). The zero point of the spatial scale coincides with the infra-red driving source. From Podio et al. (2006).

method such as the BE (Bacciotti & Eislöffel 1999) technique. The latter method is easy to apply since it makes use of the brightest optical forbidden lines i.e. [SII]$\lambda\lambda$6716,6731, [OI]λ6300, and [NII]$\lambda\lambda$6548,6584 as well as Hα. It is, however, somewhat simplistic since it assumes a uniform temperature, density and ionization fraction throughout the cooling zone and clearly this is not the case in a radiative shock. More-

TABLE 1

TYPICAL JET PARAMETERS

Parameter	Value	Units
Mass Loss Rate	$10^{-6} - 10^{-8}$	$M_{\odot}$ yr^{-1}
Neutral Density	$10^{2} - 10^{4}$	cm^{-3}
Ion Fraction	$10^{-1} - 10^{-2}$	
Flow Length[a]	$10^{-2} - 10^{1}$	parsecs

[a]Note that observed lengths are often underestimates as parts of an outflow may propagate outside the parent cloud.

over, as pointed out by Hartigan (2003), Hα emission can arise from collisions even before the shock has had a chance to cool, thus non-equilibrium effects can be important. Nevertheless, comparison of the BE technique with the more robust method of shock modeling shows that, for the typical conditions observed in HH jets, the method is adequate (Hartigan 2003).

Typical parameters that we can derive along a jet are shown in Figure 1 using as an example the HH 111 jet. Thus we can deduce fundamental parameters such as the mass loss rates, total (ion plus neutral) density, temperature, etc. In addition, through imaging, we can determine characteristic outflow length-scales (see Table 1). The latter can be large and comparable to the size of the parent cloud. In fact it seems likely that many outflows, particularly those from more evolved young stars, extend beyond their associated cloud. This fact is also readily deduced from the velocity of extended outflows and their statistically estimated lifetimes (McGroarty & Ray 2004).

Outflows are observed from a wide variety of young stars, not only of varying age (Class O to Class II protostars) but also of varying mass. They have even been observed from young brown dwarfs (Whelan et al. 2005, 2007). In the case of the most massive stars, e.g. Cepheus A (Cunningham 2006; Bally 2008) the outflow can sometimes appear less collimated. It is not clear, however, whether multiple sources, with somewhat different outflow directions, are responsible or some other phenomenon associated with the cluster phase (Bally 2008).

The detection of outflows from young brown dwarfs, down to 25 Jupiter masses, emphasizes not only the ubiquity of the outflow phenomenon but also suggests that it may occur in the case of giant planet formation. To date, direct imaging of outflows from brown dwarfs has not been possible. In fact,

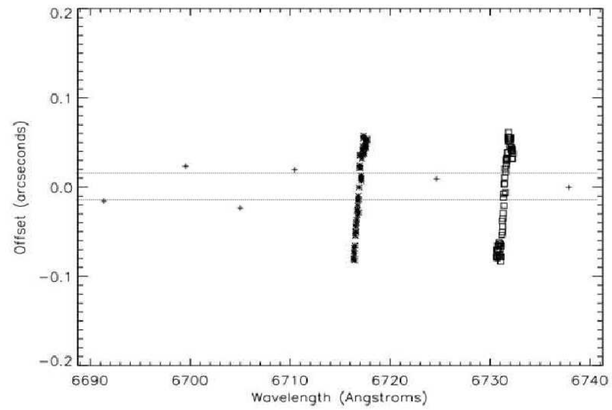

Fig. 2. Spatial offset in arcseconds from the continuum position against wavelength for the young brown dwarf ISO Cha 217 (Whelan et al., in prep.) in the region of the red [SII] doublet. The slit is positioned north-south and offsets are seen in both the blue and redshifted emission. Such offsets are mirrored in both lines as expected.

theory suggests such observations should be very challenging even with large ground-based telescopes due to faintness (Masciadri & Raga 2004). Instead the technique of spectro-astrometry (e.g. Porter et al. 2004; Whelan & Garcia 2008) can be applied. It is not possible, or appropriate, to give an account of spectro-astrometry here. Instead it suffices to say that the technique exploits the fact that line emission from a blueshifted (or redshifted) jet is spatially offset from the continuum (due to the young star or brown dwarf). The accuracy to which this offset can be measured is a function not only of the point spread function (PSF) but also of the number of photons detected. Offsets as small as 10 milliarcseconds can be routinely measured, see Figure 2.

In principle, the BE technique can also be applied close to the source, i.e., in the region where we might get the best clues to the jet launching mechanism. As expected, observed electron/total densities are higher but note that on scales of a few tenths of an arcsecond (for the nearest star formation regions), we are close to the critical density of some forbidden lines. Interestingly, in the case of bipolar jets asymmetries in the jet and counterjet are seen (e.g., Melnikov et al. 2008). Such asymmetries have nothing to do with differences in extinction: for example opening angle, total density, excitation, and velocity can differ from one side to the other. Even mass loss rates may be different in the jet and counter-jet although given the uncertainties in estimating such rates, it is difficult to be sure.

To date most of the analyses of conditions close to the source have been done using optical line diagnostic techniques. There is, however, an abundance of other suitable lines in the near-infrared that can be used instead (Podio et al. 2006; Garcia Lopez et al. 2008) and even in the mid-infrared (Dionatos et al., in preparation). Moreover, confining the analysis to optical lines precludes observations of jets from more embedded, and thus less evolved, sources. Mid-infrared studies, e.g. using Spitzer, are limited by spatial resolution although they are beginning to return very valuable information on jet parameters (Dionatos et al., in prep.). In the future, we can look forward to using facilities such as the Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope (JWST) which will have sub-arcsecond resolution (Wright et al. 2004). Near-infrared data, both imaging and spectroscopy, reveal what jet conditions are like close to Class I sources (e.g. Davis et al., in preparation). In line with molecular (e.g. SiO) data on jets from Class O sources (Cabrit et al. 2007) such outflows appear as collimated as those from more evolved sources. This underlines the fact that the jet collimation mechanism, whatever it might be, is not external (e.g., a dense surrounding envelope) but is instead somehow intrinsic to the jet (e.g. from magnetic stresses).

3. MAGNETIC FIELDS IN YSO JETS

While there is general agreement that magnetic fields play a fundamental role in launching and collimating YSO jets (see contributions of Shu 2009, and Cabrit 2009), evidence for their presence is usually indirect. Moreover, theory suggests the standard plasma β parameter is likely to vary from close to unity near the source to values $\gg 1$ for much of the jet length (Hartigan et al. 2007). In effect then jets are essentially hydrodynamic at a few hundred AU from their parent YSO. What evidence then do we have for magnetic fields? Broadly speaking this comes from several sources:

- The presence of aligned dust grains in outflows
- Observations of possible jet rotation
- Magnetic cushioning effects on jet shocks
- Non-thermal jet emission

We shall examine each of these in turn.

Recent spectroscopic observations (Podio et al. 2006; Dionatos et al., in prep.) suggest that dust is launched with jets and that it is not entirely destroyed by jet shocks, at least close to the source. For example in the jet plasma, there is clear evidence of refractory element depletion (Podio et al. 2006). Moreover such optical/near-infrared observations only probe the warm, high-velocity "spine" of the jet. There may be, for example, more dust outside this spine. In line with this suggestion, Chrysostomou et al. (2007) have detected not only dust but that its emission is circularly polarised in the HH 135/136 outflow at near-infrared wavelengths. Simulations using a 3-D Monte Carlo light scattering code show the most likely cause is aligned nonspherical dust grains in a helical magnetic field. Not only do such observations demonstrate that a magnetic field is present but also tell us something about its large-scale structure.

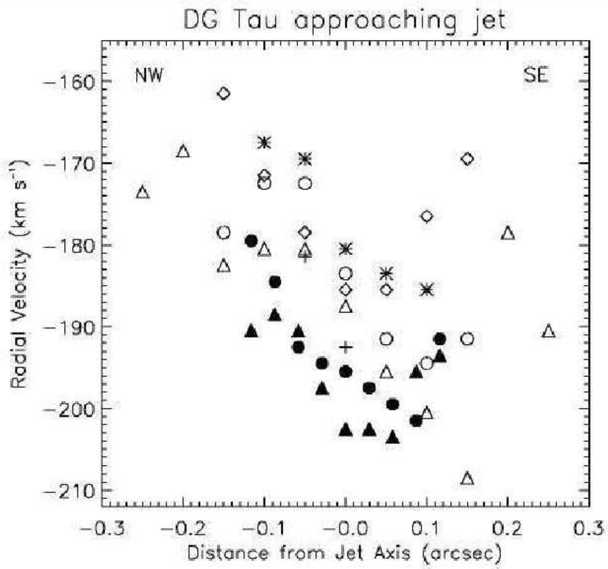

Fig. 3. Possible evidence for rotation in the DG Tauri blue-shifted jet taken from a series of UV and optical HST long-slit spectra where the slit has been placed perpendicular to the outflow direction and close to the source. Note how the radial velocity gradually increases (in absolute terms) in going from one side of the jet (negative offsets from the central axis) to the other (positive offsets from the central axis). This is seen in numerous lines including MgIIλ2796 solid triangles, MgIIλ2803 solid circles, [OI]λ6300 triangles, [OI]λ6363 circles, [NII]λ6548 asterisks, HeIλ6678, [NII]λ6583 diamonds, [SII]λ6716 squares and [SII]λ6731 crosses. Taken from Coffey et al. (2007).

Evidence for rotation in YSO jets was initially discovered using the Space Telescope Imaging Spectrograph (STIS) on board HST (Bacciotti et al. 2002). By comparing average radial velocities *laterally* across jets, consistent velocity differences from one side to the other were found of around 10–20 km s^{-1}, i.e., 5–10% of the poloidal velocity (see Figure 3). While early observations were made at optical wavelengths of neutral/ionised atomic species, similar results were found in the UV (Coffey et al.

2007) and even for the molecular component in the near-infrared (Chrysostomou et al. 2008). Assuming that we are observing rotation, there are a number of implications for the centrifugal launching of jets by magnetic fields:

- Jets extract significant quantities of angular momentum from disks. In fact rough estimates suggest they are capable of extracting all the angular momentum necessary to allow accretion to occur onto the star at the observed rates. Determination of the accretion rates has incidentally nothing to do with any outflow parameter: they are derived independently using, for example, line veiling or infrared excesses (Hartigan et al. 1995). Moreover, assuming steady MHD ejection, it is possible to use standard theory (Anderson et al. 2003) to derive the footpoints where the jet material has been launched (Coffey et al. 2007). Calculated values are around 0.5 to a few AU, thus supporting MHD disk-wind models. Another way of stating this is that the apparent specific angular momentum of jet material is consistent with it being launched from a few AU. Further observations are required however to prove beyond doubt that what we are seeing is rotation. In the case of at least one YSO, RW Aur (Cabrit et al. 2006) the sense of rotation of the disk appears to be opposite to that of the jet. This system, however, is hierarchial and clearly interacting. In particular, tidal interaction may complicate the interpretation of the dynamics.

- The jet toroidal magnetic field dominates over the poloidal field at distances of a few AU from the source (Woitas et al. 2002; Bacciotti et al. 2005). This is as expected since the observations correspond to regions well beyond the Alfvén surface where the jet's magnetic "hoop-stresses" become important and help collimate the flow.

The presence of magnetic fields can also be inferred using line diagnostics of the radiative zones behind jet shocks (Hartigan et al. 1994). In particular, the toroidal (transverse component) of the field will be compressed, and thus increase, as the density builds up. Since the gas tries to maintain pressure in the post-shock zone, it is easy to see that $\beta \propto T^{-2}$ where T is the temperature. This raises the possibility of magnetic pressure dominating, or at least becoming significant, as the gas cools. One dimensional models (Hartigan et al. 1994) show that the cooling length, and hence longitudinal extent, of forbidden emission behind a shock changes with magnetic field strength. While extracting precise field strengths is difficult, observed values seem to be in line with predictions (Hartigan et al. 2007). In other words, the

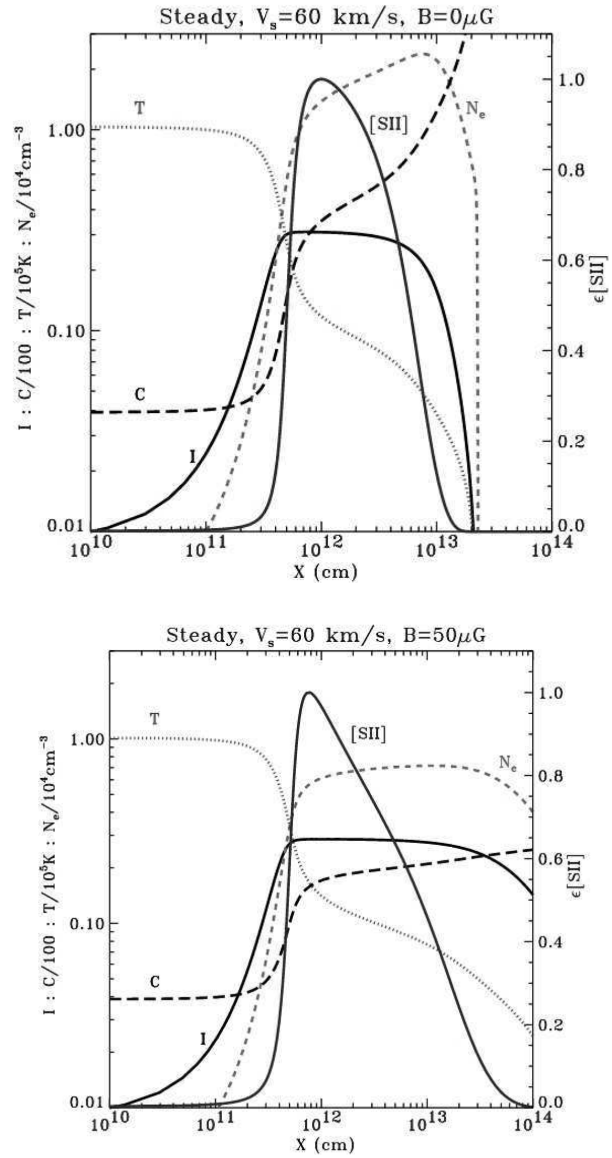

Fig. 4. Cushioning effect of a transverse magnetic field on a radiative shock. Top panel shows how the temperature (T), compression (C), electron density (N_e) and [SII] emission varies across a non-magnetic shock. Corresponding quantities are shown in the bottom panel when a pre-shock transverse magnetic field of strength B=50 μG is included. In both cases the velocity of the shock is assumed to be 50 km s^{-1}. Adapted from Hartigan (2003).

jet magnetic field is not dynamically important at several hundred AU from the source although it may set a limit to the compression that can be achieved in the post-shock zone (see Figure 4).

A last possible measure of the magnetic field in YSO jets could come from their radio emission. Almost all such emission is thermal, weak and unpolarized. There are, however, a number of cases of known, or suspected, outflows with non-thermal radio emission (e.g., Ray et al. 1997; Girart et al. 2002). Non-thermal emission associated directly with young stars is well-known (e.g., Skinner 1993) but this is almost certainly a surface phenomenon possibly associated with flares. From the perspective of obtaining a handle on the jet's magnetic field, we are more interested in extended non-thermal structures at least $0\farcs1$ to $1''$ from the star. Ideally, we would like to measure any polarisation, a task that is not made easy by the typical radio weakness of these sources. The situation will improve in the near-future with the availability of instruments such as LOFAR (Röttgering 2003) and e-MERLIN (Garrington et al. 2004). LOFAR will be able to probe emission at low radio frequencies ($\approx$100 MHz) where any non-thermal radio emission might be expected to dominate. Moreover, it will be able to do this with arcsecond spatial resolution. The radio interferometer e-MERLIN, while operating at normal frequences, promises enormous gains in sensitivity, due to the use of broadband fiber optic links. Thus faint, non-thermal emission can be searched for.

It should be emphasized that any non-thermal emission may not necessarily be synchrotron. It could, for example, be gyro-synchrotron (Ray et al. 1997) which is circularly, rather than linearly, polarized. The only measurement of magnetic fields to date in an outflow (Ray et al. 1997) suggests relatively strong fields ($\approx$ 1 Gauss) at distances of around 10 AU from the source. Note, however, that such fields are likely to have been amplified by shock compression.

4. CONCLUSIONS

All parameters, with the exception of the magnetic field, are well determined in YSO jets. The magnetic field, however, is not thought to be important except close to the source (i.e. only within a few hundred AU at most). Thus, hydrodynamic models for the propagation of jets, once they include proper initial and boundary conditions, could be realistic approximations of what we observe.

There is plenty of indirect evidence for magnetic fields in outflows including aligned dust grains, possible jet rotation and cushioning of jet shocks. If the lateral differences in radial velocities across jets is confirmed to be rotation, then it suggests most, if not all, transport of angular momentum necessary to maintain disk accretion, is done through the disk magnetic field and the outflow.

Currently, there are very few direct measurements of magnetic field strengths, and none of direction, in YSO jets. The situation may change in the future with the next generation of radio instruments such as e-MERLIN, LOFAR and ultimately the Square Kilometer Array (SKA).

Much of the work discussed here was carried out within the Jet Simulations, Experiments and Theory (JETSET) Marie Curie research training network under European Union contract MRTN-CT-2004 005592. TPR would also like to acknowledge the very kind hospitality of the conference organisers.

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