Mem. S.A.It. Vol. 76, 362

Memorie della

Outflows from low mass young stars and brown dwarfs

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Abstract. The phenomenon of jets from young stars has been known for over two decades. In most cases the jet is generated either by an embedded (IRAS Class I) low mass star or its more evolved, optically visible counterpart (a classical T Tauri star). In the case of the latter the flow can be traced optically right back to the star although its apparent length may be small in angular terms (typically a few arcseconds). For this reason such jets are sometimes referred to as "micro-jets". It is argued that brown dwarfs (BDs) outflows, when observed will almost certainly look like scaled-down versions of the micro-jet phenomenon observed in classical T Tauri stars. Not only then will we need large telescopes to detect such flows but it may also be necessary to employ special techniques, like spectro-astrometry, to resolve them.

Key words. Young stars – brown dwarfs – outflows – Herbig-Haro objects – jets

1. Introduction

It is now over twenty years since the discovery of jets from young stars. Since their discovery we have made enormous strides in understanding their propagation on large (hundreds of AU to parsec) scales (Eislöffel, Mundt, Ray, & Rodríguez 2000). This has been aided by a plethora of line diagnostics so that not only are basic parameters, such as velocity and temperature, well known but also quantities like density and degree of ionisation Bacciotti et al. (2003). Thus these jets are well characterised, unlike perhaps their extragalactic counterparts, with the exception of one, presumably important parameter, the strength of their magnetic fields.

Although the outflow phenomenon is associated with a wide range of young stellar object (YSO) masses, most of the known outflows are generated by low (i.e. solar-like) or intermediate mass stars. Here I review some of properties of optical outflows before considering how best we might observe jets in the case of very low mass young stars and brown dwarfs (BDs).

2. Setting the Scene

Most of us are now very familiar with the beautiful images in the literature of jets from young stars. These jets are sometimes referred to as Herbig-Haro (HH) jets following their close association with the nebulous knots, or HH objects, discovered in the 1950s. Many HH objects in fact turned out to be either knots within a jet or, more usually, the bright "terminal" bow shock where a jet rams into its surround-

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ings, e.g. HH 34S. Both HH objects and jets radiate via line emission. These lines are generated in the cooling zone of shocks rather than through photo-ionised emission (Hartigan 2003). Although permitted lines, e.g. Hα, are produced, forbidden lines, e.g. [OI]λ6300 and [SII]λ6731, act as powerful tracers of jets. Spectroscopic observations of such lines reveal radial velocities that are typically 100-300 kms^{-1}, thus these jets have velocities that are characteristic of the escape velocity from their parent star. Although jet velocities are a few hundred kms^{-1}, the actual measured shock velocities (gauged, for example, from various line ratios) are usually much smaller. The only exception are the "terminal" bow shocks, such as HH 34S, where a significant proportion of the jet's bulk kinetic energy appears to be converted into thermal energy and then radiated away. Why are the typical shock velocities observed much lower (typically a few tens of kms^{-1})? The simplest explanation is that they represent "internal working-surfaces" where faster moving material in the jet catches up with slower moving material and this gives rise to shocks with strengths that are approximately equal to the *velocity difference* (Raga, Canto, & Cabrit 1998). Note that these jets are highly supersonic, with Mach numbers in the range 10-30, thus it only requires an increase, for example, of 10% in the outflow velocity to generate such a low excitation shock.

YSO jets are highly collimated, with opening angles typically of at most a few degrees (Mundt, Ray, & Raga 1991). Thus although they may, at least in some cases, be confined by external pressure, jet opening angles are close to the free expansion values i.e. $\theta_{Opening} \approx 1/M_{\rm jet}$ where $M_{\rm jet}$ is the jet Mach number. This degree of collimation can persist over the entire observable length of a outflow, e.g. several parsecs. Moreover, it has proved possible to resolve these jets transversely in a number of cases, although sometimes this requires the spatial resolution afforded by the HST (Bacciotti et al. 2002). Finally we can measure the mass loss rates of these jets. Typically values are found to be 10^{-8}–10^{-6} $M_\odot$ yr^{-1} although clearly this depends not only on the mass of the star, as one might imagine, but also on its state of evolution. Thus, for example, all else being equal, Class I YSO jets have higher mass loss rates than those from less embedded Class II sources such as classical T Tauri stars, hereafter referred to as CTTSs (Calvet 1997).

While the propagation of YSO jets is well understood, considerably less is known about their origins. The general consensus is that they are launched centrifugally along magnetic field lines that are anchored to a disk. Two rival theories however exist that propose alternative launching zones: the X and D-wind models (Shu, Najita, Shang, & Li 2000; Konigl & Pudritz 2000). In the case of the former this zone is at the co-rotation radius of the disk, i.e. where the disk co-rotates with the magnetosphere of the star. In the latter, the wind is centrifugally launched from the whole disk. Subsequent collimation is then achieved through magnetic hoop stresses. Which of these two scenarios is correct is still debatable although recent observations of rotation in YSO jets (see Bacciotti et al. these proceedings) would appear to support the disk wind model. Moreover it appears that most, if not all of the angular momentum lost by matter accreting through the disk could end up in the outflow.

Turning now to young brown dwarfs (BDs), how might we detect their outflows, assuming such outflows are present? To date most of the known BDs have been found through NIR/optical surveys, (López Martí, Eislöffel, Scholz, & Mundt 2004,for example) and, since these objects do not have a main sequence phase, it is easier to find them when they are relatively young in regions like Ophiuchus and Taurus. Moreover there is ample evidence that BDs are surrounded by accretion disks based on their NIR colours (Jayawardhana, Ardila, Stelzer, & Haisch 2003). In order, however, to currently identify a target as a BD we must see its photosphere directly. This means that the nearest analog we might expect to BDs with outflows are the low mass IRAS Class II YSOs i.e. CTTSs. The similarities in spectroscopic properties of BDs and CTTSs is striking (see Jayawardhana et al. and Luhman et al., these proceedings). Thus it is instructive to look at outflows from the latter to get some guidance as to what we might expect to find in BDs.

By and large optical outflows from CTTSs, with few exceptions, are not as spectacular as those from more embedded sources (e.g. HH 34 IRS). The "exceptions" tend to be those borderline IRAS Class I/II objects, such as DG Tau. Where seen such outflows often consist of a "micro-jet" i.e. a few arcsecond long jet (Dougados, Cabrit, Lavalley, & Ménard 2000) that, in a number of cases, is barely resolved in the outflow direction (Hirth, Mundt, & Solf 1997). Of particular interest is the fact that CTTS micro-jets can normally be traced optically right back to their source, something that is not possible in the case of outflows from Class II sources (Whelan, Ray, & Davis 2004). Thus, if outflows from optically visible BDs exist, it is most likely that they also produce "micro-jets" and that, like those from CTTSs, the brightest emission is closest to the source.

How bright might we expect BD micro-jets to be? In a recent paper, Masciadri & Raga (2004) have pointed out that the luminosity of any BD jet should roughly scale with the mass outflow rate, assuming the jet is not photoionised. Now as stressed by Luhman (these proceedings), the mass accretion rate varies approximately with $M_{*/BD}^{-2}$ where $M_{*/BD}$ is the mass of the star or BD. Thus mass accretion rates, and by inference mass outflow rates, in BDs are at least 10^{-2} times smaller than those in solar-mass CTTSs. Since the nearest locations with young BDs are also the same regions with CTTSs, any outflow from a BD might be expected to be 10^{-2} times fainter than those from CTTSs and thus only observable with very large ground-based telescopes.

A method that has proven to be extremely useful not only in finding faint outflows from CTTSs but also in determining their characteristics is spectro-astrometry (Takami et al. 2001). Potentially this technique has application in searching for outflows from BDs and in particular those in which we know forbidden lines, usually a signpost of an outflow (see Luhman these proceedings), are present.

Spectro-astrometry is relatively easy to understand. The best resolution we can achieve from a telescope is determined either by the Rayleigh criterion, in the case of a small telescope or, for larger systems, by the seeing if the telescope is ground-based. Now suppose the image of a star is smeared by the atmosphere, then the width of the stellar image, which is approximately a gaussian, defines the seeing. While the width cannot be reduced without resorting to adaptive optics, the centroid of the emission can be determined to increasingly higher accuracy by lengthening the exposure, i.e. by increasing the number of detected photons N. This of course assumes that the detector scale is such that the point spread function (PSF) is at least Nyquist sampled or even better somewhat oversampled. Now suppose the star we are observing is not a single star but a closely separated binary with virtually identical components. Let us further assume that the separation between the stars is much less than the seeing and that we observe the system spectroscopically with the slit orientated along its position angle. We will, of course, see what appears to be one continuum in the dispersion direction and the emission centroid of this continuum will be located exactly between the two stars. Now suppose one of the stars differs from the other in only one respect: it is a strong Hα emitter (a somewhat artificial situation!). Then the emission centroid, determined by fitting a gaussian in the spatial direction, will be shifted *towards* the Hα emitting star at the position of the Hα line. Measuring the shift allows us, in effect, to "resolve" the binary. The situation is slightly different if we are observing a BD or CTTS with a micro-jet. We are then, in effect, dealing with a continuum source, the BD or CTTS, and a pure emission line component. Now although the latter can be observed to be perhaps a few arcseconds long (at least in the case of the brightest micro-jets from CTTSs) the centroid of the emission is much closer to the star i.e. this is the region where the jet is brightest. Moreover in the case of the forbidden lines, the position of the centroid is in large part set by the location where the jet electron density reaches the critical value for the observed line (for example about $10^4 \mathrm{cm}^{-3}$ in the case of the red [SII] doublet). For CTTS outflows, the spatial offset values therefore vary somewhat depending on the line (see Hirth et al. 1997) but, in angular terms for the nearest star forming regions, they are typically 0.5 – 1.0 arcseconds i.e. at or below the typical seeing. What offsets might we expect in the case of BDs? As shown by Masciadri & Raga (2004), jet velocities from BDs are expected to be similar to those from CTTS. Since they will produce shocks, presumably in the form of internal working surfaces as with CTTS jets, we expect the shocks to cool to 10^4K i.e. for the sound speed in BD outflows to be the same. Now if their sound speed and velocity are the same, we expect their opening angles to be similar since the angle (in radians) is around $1/M_{Jet}$ where M_{Jet} is the jet Mach number. If we assume, somewhat naively, that the jet is a uniform conical flow to a first approximation, then the density, all else being equal, is determined by $\dot{M}_{Jet}{}^{0.5}$. As the accretion rates in BDs are, at most, 2×10^{-2} those in CTTSs, we would therefore expect any forbidden emission line offsets in BDs to be perhaps 5-10 times smaller than those seen in CTTSs. Measuring such small offsets are well within the capabilities of spectro-astrometry using very large telescopes.

3. Conclusions

Magneto-centrifugal launching of a wind, and subsequent focussing into a jet, seems the most likely explanation for the highly collimated outflows we see from young stars. It seems probable that BDs also produce jets, not unlike their higher mass counterparts the classical T Tauri stars. Any jet from a BD however is likely to be very faint indeed and difficult to observe. Moreover since such jets tend to fade rapidly with distance from the source (although they may subsequently brighten up at a more distant working surface), any emission will be confined to the region immediately surrounding the BD. Under these circumstances, spectro-astrometry offers the best opportunity of discerning such a flow.

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