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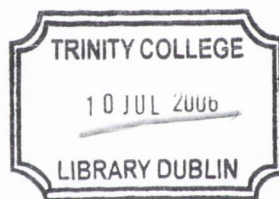
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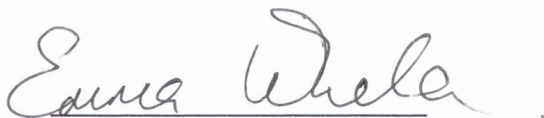
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Emma Whelan

Dublin March 2005

Summary

The phenomenon of mass outflow from young stellar objects, is arguably the most spectacular stage in the formation of a star. Much is known about the large scale manifestations of outflows and many breathtaking images attest to the energetic nature of their interactions with their parent molecular clouds. However, in comparison to what is known on the large-scale, the mysteries of the central engines of young stars from which the outflows are launched, are little understood. A lot of the knowledge concerning protostellar jets close to their point of origin (the jet launch region) comes from the study of the forbidden emission lines (FELs) of one group of protostars in particular, the low mass optically visible Classical T Tauri stars. Traditionally probing the region of the central engine has proved difficult. Direct imaging for example is challenging due to contamination by stellar radiation. Intermediate resolution spectroscopy helps to overcome this problem however the spatial resolutions achievable are not satisfactory. If a true understanding of the central engine is to be attained information must be recovered on the smallest scales possible.

The nature of the protostars themselves can also impede such studies. For example, the youngest and least evolved sources, tend to be deeply embedded and thus optically invisible. Traditionally however the highest spatial resolution studies were only conducted at optical wavelengths. The aspiration of this thesis project is to use the pioneering technique of spectro-astrometry to overcome the limitations placed on spectroscopic observations by the spatial resolution and thus probe outflow activity as close to the central engines of a range of objects from the sub-stellar to intermediate mass regimes, as possible.

Chapters 1 and 2 are introductions to the subjects of outflows from young stellar objects and spectro-astrometry. Chapter 3 is concerned with low mass Class I sources. The aim of this study was to investigate if near-infrared FELs were as

effective at tracing outflow activity close to the central engines of these embedded sources as the optical FELs are for the Classical T Tauri stars. A combination of long-slit spectroscopy and spectro-astrometry revealed that the [FeII] $1.644\mu\text{m}$ is as useful a probe of the central engine as the optical [SII] $\lambda 6731$ line say and the disk-wind model can also be used to explain the FELRs of Class I sources.

In Chapter 4 the central engines of a sample of CTTSs are probed using the near-infrared Paschen beta line ($1.2822\mu\text{m}$) rather than the optical FELs. This line forms much closer to the driving source than the FELs, thus it maps the central engine on a much smaller scale. However it is believed that permitted HI lines mainly trace the infall of material onto to central star and disk. Spectro-astrometry is used to demonstrate that Pa β can trace outflow activity in CTTSs. This result is important as it demonstrates that spectro-astrometry is an effective means of disentangling the outflow contribution in HI lines. In particular results also point to the presence of a dust hole in the disks of two of the sources.

Chapter 5 concentrates on the intermediate mass Herbig Ae/Be stars. The FELRs of these protostars have been studied previous to this work however the spatial properties of the FELRs have not been accurately mapped. This is the main goal of Chapter 5. Results confirm that the disk-wind model is applicable to the central engines of higher mass sources. The same technique adopted in Chapter 4 is used to again uncover dust holes in the disks of two of the Herbig Ae/Be stars. Lastly in Chapter 6 it is shown that spectro-astrometry can be used to probe the FELRs of brown dwarfs proving for the first time that they can drive outflows. No outflow from a sub-stellar object has yet been imaged and the only suggestion previous to this study that they may be associated with outflows is the presence of strong FELs in the spectra of some sub-stellar sources.

Overall this thesis demonstrates that spectro-astrometry can be used to reveal new and exciting information about the central engines of objects from which outflows are launched. The discovery that spectro-astrometry can detect outflows from brown dwarfs is particularly important. It is now apparent that outflows are driven by, not only massive black holes at the centre of active galaxies but by brown dwarfs which are around ten million times less massive, as well. Hence the outflow mechanism is a common feature of objects that are accreting material onto a disk, regardless of the nature of the accreting body. In Chapter 7 the overall conclusions that can be taken from the work presented here and the many ways in which this work can be built on and improved in the future, are discussed.

Publications

Davis, C. J., Whelan, E., Ray, T. P., Chrysostomou, A., 2003. **Near-IR echelle spectroscopy of Class I protostars: Mapping Forbidden Emission-Line (FEL) regions in [FeII].** A&A 397, 693

Whelan, E. T., Ray, T. P., Davis, C. J., 2004. **Paschen beta emission as a tracer of outflow activity from T-Tauri stars, as compared to optical forbidden emission.** A&A 417, 24

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For Teresa and Barry
and Carmel

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Chapter 1

An Introduction to the Formation and Study of Protostellar Outflows

Before the invention of the telescope the only tools available to those inquisitive enough to wonder about the universe around us were their eyes and their imaginations. To them the night sky appeared flooded with millions of stars and the fundamental question they must have asked themselves is “*Where do the stars come from?*” Modern day astronomers have the technology to penetrate far beyond our solar system, and can now easily discriminate between the different types of objects that crowd our vision as we gaze out at the night sky. However one of the quintessential questions driving the quest for astronomical knowledge still remains “*How do the stars form ?*”. There are many aspects to the study of star formation from the initial conditions required, to the different stages that protostars pass through before hydrogen fusion commences and the resultant star joins the main sequence. In this thesis I am concerned with the *outflow stage* when new stars collapsing under their own weight, launch powerful bipolar outflows which plough through and strongly interact with the molecular clouds in which they are born. In particular the aim of this body of work is to provide new observations of outflows close to their point of origin. Observations of the “jet launch region” are vital to firstly, constrain the models which attempt to explain how jets are launched and become collimated with $\sim 100\text{AU}$ of their driving source and secondly, to provide an understanding of the structure of the jets on such small scales.

CHAPTER 1. Outflows from Young Stellar Objects

The stages in the formation and development of a new star, similar to our own sun, are represented in Figure 1.1. Stars form through the gravitational collapse of molecular cores. Initially the cores are supported against collapse by turbulence and the effects of magnetic fields (see section 1.1.1). However magnetic and turbulent support can be lost through ambipolar diffusion and once the balance between the internal pressure of the fragment and gravity is disturbed the stellar mass cloud begins to collapse at the free-fall rate (Shu, Adams, & Lizano, 1987; André et al., 2000). Initial collapse is the first stage in the formation of a star. As it falls down its own gravitational potential well huge amounts of energy are released which goes into the random motion of the gas particles heating the collapsing cloud. At first densities are low and most of the radiation can escape but as collapse proceeds the radiation becomes trapped and the interior of the cloud heats up. A temperature gradient and hence an internal pressure gradient form which begin to resist collapse. When the stage where this pressure gradient nearly balances gravity is reached contraction continues at a slow rate that is just enough to balance the rate of energy loss from the surface by radiation. A protostar has formed. As the centre of the protostar is hotter and denser than the material close to the surface the interior achieves the state of quasi-static equilibrium before the exterior. A core halo structure with a slowly contracting central core surrounded by a infalling envelope, is the result. Some material accretes onto the central star and some onto an accretion disk. Stage 3 is the bipolar outflow phase. The accretion of material combined with the rotation of the protostar causes the launching of powerful bipolar outflows, which drive away the circumstellar material that encompasses the protostar. The final stage before the star joins the main sequence involves the slowing down of accretion processes and thus outflow activity. The protostar is surrounded by a circumstellar disk which is undergoing the first stages of planet formation.

Obviously the description given above is a very much simplified version of the star formation process. However the aim of this chapter is to explain in greater detail the most important aspects of stellar birth, concentrating mainly on the outflow phenomenon. The topic of giant molecular clouds (GMCs) is briefly introduced in section 1.1. In section 1.2 the most common and well studied large and small-scale manifestations of protostellar outflows are reviewed. Special attention is paid to models describing the formation of jets and to observations of them on scales comparable to the size of the central engine. An important aspect of the results presented in this thesis are that they are based on observations of different categories

CHAPTER 1. Outflows from Young Stellar Objects

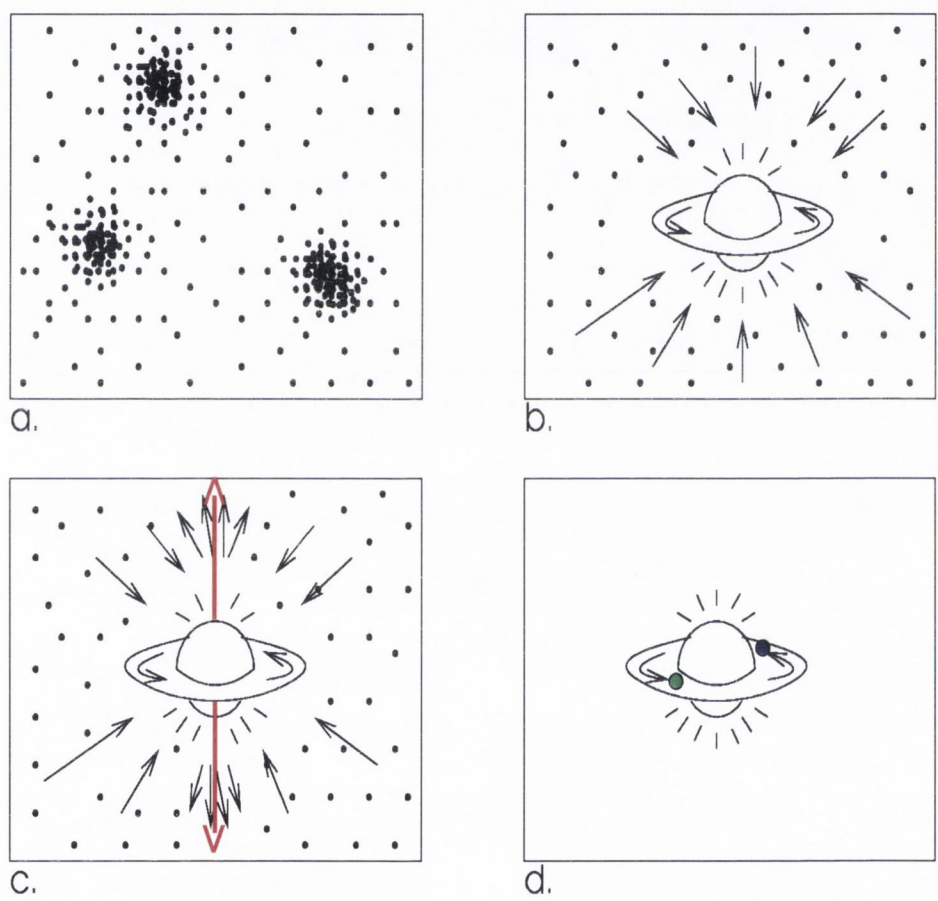


Figure 1.1: The different stages in the formation of a star. a) pre-stellar cores embedded in a molecular cloud begin to collapse, b) A core halo structure with a slowly contracting central core surrounded by an infalling envelope is quickly achieved, c) A powerful outflow is launched, d) accretion and outflow activity slows down to leave a new star surrounded by a circumstellar disk in which planets begin.

CHAPTER 1. Outflows from Young Stellar Objects

of young stellar objects (YSOs) which are essentially divided according to mass and evolutionary stage and on observations of Brown Dwarfs (BDs). In section 1.3 these categories are defined and discussed and a description of the properties of the outflows that they drive or, as in the case of the BDs, are predicted to drive is given.

1.1 Stellar Nurseries

The Giant Molecular Clouds (GMCs) which make up a substantial fraction of the Interstellar Medium (ISM) are the birth places of most stars and are in effect the *Stellar Nurseries* of the Milky Way¹. The question of how stars form in molecular clouds must begin with a thorough understanding of the physics of the clouds themselves, in particular their structure. Williams et al. (2000) list some of the basic properties of a GMC. They have masses of $\sim 10^5\text{--}10^6 M_\odot$, diameters of $\sim 50\text{--}100$ pc and average densities of $\langle n_{H_2} \rangle \sim 10^2 \text{ cm}^{-3}$. To summarise; they are the most massive and coldest objects in the universe, are composed almost entirely of molecular hydrogen, contain significant amounts of interstellar dust and are permeated by magnetic fields with strengths in the range $10 - 20 \mu\text{G}$ (Lada, 1996). Most of the information that we have about molecular clouds is derived from observations of the CO, CS or NH_3 molecules.

An important feature of GMCs is that they are strongly gravitationally bound thus allowing them to survive long enough to give birth to several generations of young stars. How exactly they achieve this state is not entirely known as thermal pressure alone cannot support against global collapse, although it is certain that magnetic fields and turbulence play a vital role (Padoan et al., 2004; Vazquez-Semadeni et al., 2000). Cloud turbulence, even in the presence of magnetic fields, dissipates too quickly compared to typical cloud lifetimes however, (Stone et al., 1998) and must therefore be somehow replenished. One suggestion is that the powerful outflows driven by the newly forming stars may generate enough turbulence as they travel through the molecular cloud to sustain the overall turbulence in the cloud (Fukui et al., 1993; Henning, 1989).

An obvious example of a nearby GMC is Orion, a much studied region of intense

¹Note that stars are also born in Small Molecular Clouds (SMCs) such as Taurus-Auriga or Ophiuchus. Much of what is described here is also pertinent to SMCs (see Lada et al. (1993) for a more thorough discussion).

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star formation. It is relatively close ($d \sim 450$ pc) and it has a good mix of low and high mass stars, making it a particularly convenient place to study young stars. Indeed the first candidate protostars were discovered here, as well as most interstellar molecules (Genzel & Stutzki, 1989; Becklin & Neugebauer, 1967; Jefferts et al., 1970). The Orion region can be divided up into two large molecular cloud complexes, Orion A and Orion B (named after the most prominent HII regions within them) which are the primary sites of active and most recent star formation. Located towards the northeastern edge of the Orion A cloud, in Orion's sword is the Orion Nebula (M42), shown in Figure 1.2. This nebula harbours the nearest place in our galaxy where high-mass stars are being formed and is perhaps the most intensely studied region of star formation. In Figure 1.4 I show one of the many images taken of this stellar nursery. A singularly remarkable feature of this nebula, are the so called Orion "bullets". These fast moving regions of shocked emission, first discovered by Allen & Burton (1993) are located at the head of "fingers" of H₂ emission. They are part of a highly uncollimated flow from a massive star (Graham et al., 2003). Figure 1.5 is an image of this uncollimated flow in the near-infrared, taken with IRIS on the Anglo-Australian telescope (AAT).

1.1.1 Clouds, Clumps and Cores

The structure of a molecular cloud is inextricably linked to the processes of star formation taking place within it. This structure can be loosely categorised into clouds, clumps and pre-stellar cores (Williams et al., 2000). Molecular clouds as described above can have many sites within them where new stars are being born. Clumps are in effect the building blocks of molecular clouds and are generally identified from spectral line maps of molecular emission. A comparison between the internal kinetic energy of a clump and its gravitational potential energy allow it to be classified as being gravitationally bound or unbound. If the internal kinetic energy which is primarily generated by turbulence, balances the gravitational potential energy the clump is bound. Gravitationally unbound clumps can be pressure bound in that the additional pressure created by the internal turbulence may be balanced by the mean pressure of the ambient medium. Pressure bound clumps tend to be transient structures, (Vazquez-Semadeni et al., 2000), whereas star-forming clumps are gravitationally bound and are the regions in molecular clouds that form the stellar clusters in which most stars are born (Williams et al., 2000).

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Figure 1.2: The Constellation of Orion. M42 located in Orion's "sword" is highlighted within the yellow box.

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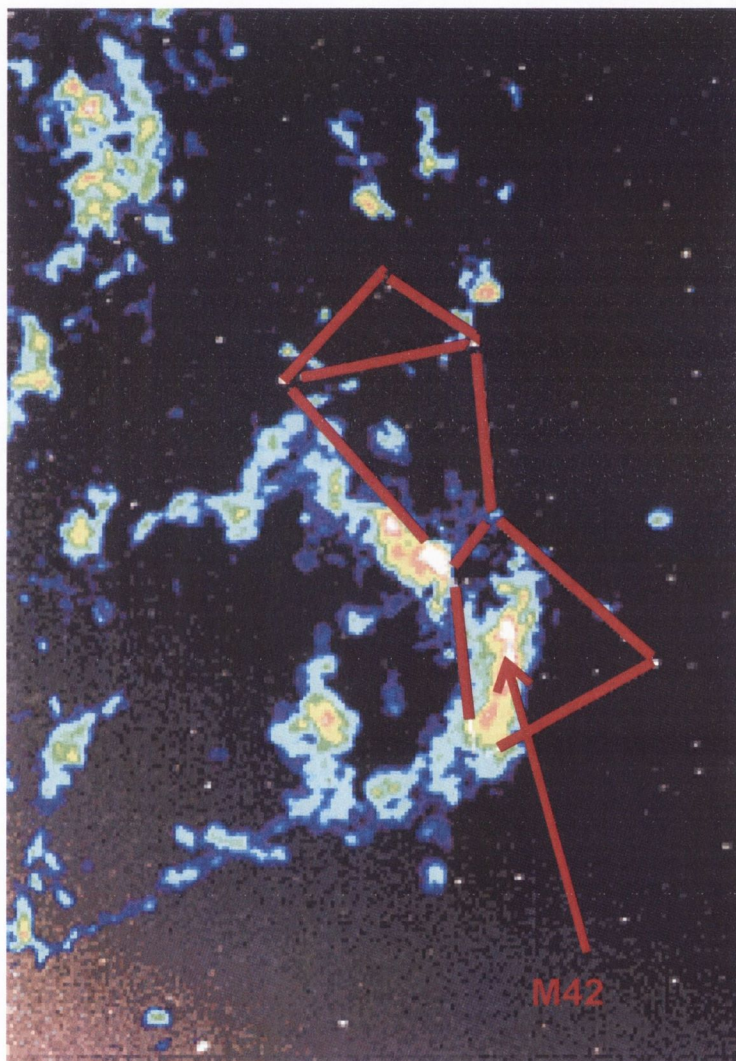


Figure 1.3: A CO map of the dense molecular gas of the Orion GMC complex, superimposed on an optical image of the Orion Constellation. The CO map was obtained with the 1.2 meter Millimeter-Wave Telescope at the Harvard-Smithsonian Center for Astrophysics, over the course of several years. Note how M42 lies in the densest part of the GMC.

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Figure 1.4: A colour composite mosaic image of the central part of the Orion Nebula, based on 81 images obtained with the infrared multi-mode ISAAC instrument on the ESO Very Large Telescope (VLT), at the Paranal Observatory. The famous Trapezium stars which are massive hot stars that illuminate the nebula are seen near the centre and the image also shows the associated cluster of about one thousand stars young stars, which are about a million years old.

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Figure 1.5: The “fingers” of H_2 emission and “bullets” in Orion. This near-infrared image of this uncollimated outflow was taken with IRIS on the AAT (Lee & Burton, 2000). The H_2 emission at $2.12\ \mu\text{m}$ is shown in red and the $[\text{FeII}]$ emission at $1.644\ \mu\text{m}$ in green.

Pre-stellar cores are the small cold fragments of stellar mass out of which individual stars or multiple systems (binaries) are born. These initially gravitationally bound condensations form when molecular clumps fragment, perhaps due to ambipolar diffusion, the dissipation of turbulence, or an outside force (André et al., 2000). Ambipolar diffusion is the process whereby the clumps uncouple from the interstellar magnetic field, which would otherwise resist their gravitational collapse². Once the cores themselves become gravitationally unstable they begin the process of collapse and an actively accreting protostar quickly forms at their centre. It is still uncertain exactly what initiates collapse in these stellar fragments, however the existence of a collapse phase following the initial fragmentation of the molecular cloud clump, and prior to the main accretion phase, is predicted (André, 2001). Cores are divided into Class 0 objects and starless cores, depending on whether they harbour an accreting protostar or not. A large number of pre-stellar cores have now been observed, both in molecular line tracers of dense gas such as NH_3 , CS , N_2H^+ and

²More precisely ambipolar diffusion is the process whereby the ions, coupled to the magnetic field, slip with respect to the neutrals. The neutrals being inexorably drawn inwards by the increasing gravitational force.

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HCO⁺ (André et al., 2000) and in the sub-millimetre dust continuum (Kirk et al., 2002). Research in the field of pre-stellar cores is driven by the need for a greater understanding of the pre-collapse phase as well as the initial stages of collapse.

1.2 The Outflow Stage

The phenomenon of mass outflow dominates for $\sim 10\%$ of the pre-main sequence phase of a typical solar mass star. This highly energetic process manifests itself in several different forms and on many scales. Thus outflow activity can be probed across the electromagnetic spectrum from radio to x-ray wavelengths. Figure 1.6, taken from Reipurth & Bally (2001) illustrates the most common forms of emission associated with protostellar outflows and their degree of excitation. The majority of these tracers are excited by shocks, that are either driven into the molecular cloud by a highly collimated jet or driven into the jet itself. For embedded stars the jet is difficult to observe directly, and in this case outflows are mainly studied through their interactions with their parent molecular clouds. On the largest scales, outflows as traced by molecular flows and Herbig-Haro (HH) objects (see section 1.2.1) are often seen to be several parsecs long (McGroarty et al., 2004a; McGroarty & Ray, 2004b; Reipurth & Bally, 2001). In contrast, for the least embedded sources, we can explore using long-slit spectroscopy the primary jet on scales of $1''$ from the source (Eisloffel et al., 2000; Davis et al., 2003; Whelan et al., 2004). A simplified model unifying the prime manifestations of outflow activity, describes how the fast collimated jet excites the nebulous HH objects and drives the circumstellar molecular gas outwards in the form of molecular flows (Bachiller, 1996).

In this section I shall firstly discuss outflows on large scales (10^3 - 10^6 AU), as seen for example in the form of giant HH flows and molecular lobes. Observations in this range attest to the claim that the outflow phenomenon is arguably the most spectacular feature of the star formation process. As stated, the aim of my work is to recover information of jets on scales comparable to the size of the central engine (~ 100 AU). Hence I shall introduce the topic of small scale ($< 10''$ in angular terms typically) stellar jets, and describe how they have been observed to date, what these observations tell about conditions and activity in the jet launch region and the models explaining their launch and collimation.

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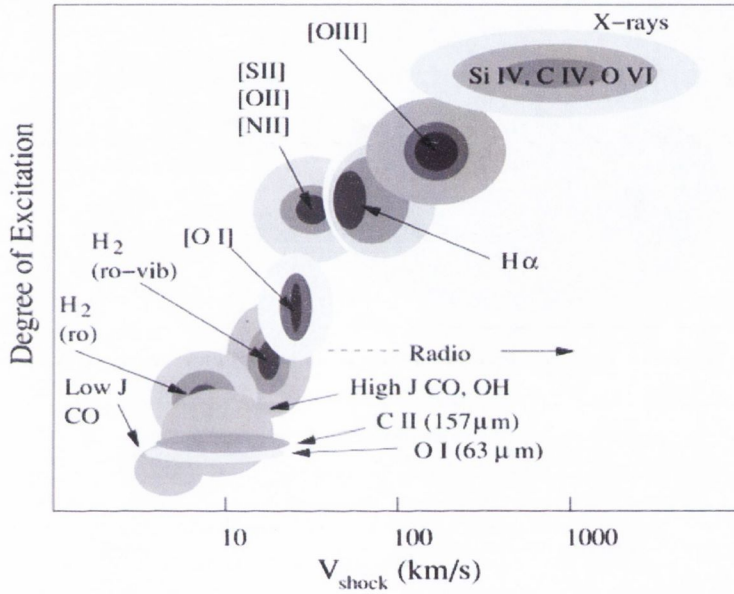


Figure 1.6: Illustration of the degree of excitation of the most common emission lines associated with outflow activity, taken from Reipurth & Bally (2001). The lower rotational (low- J) states of CO are thermally excited throughout the swept-up gas at the ambient temperature of a typical molecular cloud (~ 10 K). The radiation from warm (~ 50 – 200 K) postshock gas is dominated by the $63\text{-}\mu\text{m}$ O I and $157\text{-}\mu\text{m}$ C II lines. Emission from molecular gas in postshock layers with temperatures of ~ 200 – 2000 K is dominated by high- J CO and OH emission, and by the pure-rotational and the ro-vibrational states of H₂. The neutral and singly ionised forbidden optical emission lines appear behind faster ($>30\text{ km s}^{-1}$) shocks where the 2-eV collisions needed to pump these transitions occur. The near-infrared [Fe II] emission can be excited by somewhat slower shocks.

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1.2.1 Herbig-Haro Objects as tracers of highly collimated outflows from YSOs

HH objects are generated either by the interaction of an outflow with its parent cloud or itself. They are the post-shock cooling zones of radiative shocks and have characteristic line emitting spectra. Some are bow shaped, others have a jet like morphology, while most have simply random shapes. The idealised image of HH object is of a well-collimated jet ending in a bright symmetric bow shock and while such perfect objects are rare some examples do exist. HH 34S is one such example of a HH object with a morphology consistent with an idealised bow-shock model (see Figure 1.7 and 1.8). Numerous factors including, individual environments, varying evolutionary stages and differing extinction combine to influence the morphology of HH objects.

Herbig (1951) and Haro (1952) independently observed these phenomena and although their association with star-forming regions was obvious from the beginning they were far from understood. It was not until the work of Schwartz (1975) that it was realised that they were caused by high velocity outflows from new stars. Schwartz (1975) noted that the spectrum of a typical HH object resembled the spectrum of a supernova remnant, leading him to propose that HH emission was due to radiative shocks caused by outflows. Hence they provided some of the first clues for the existence of an outflow phase in the formation of a star. Initially outflows from YSOs were believed to be spherically symmetric however the discovery of YSO jets in the early 1980s contradicted this belief and changed the interpretation of HH objects (Mundt & Fried, 1983; Mundt, Brugel, & Bührke, 1987). See also Schwartz (1983) and Böhm (1983) for early reviews. The importance of these small nebulous objects lies firstly in the fact that they are optically visible. As they are bright in optical emission lines they are easily detected and hence are strong signposts of star formation in regions where the protostars themselves are deeply embedded and thus optically extinct. Secondly, the morphology and kinematics of HH objects in parsec-scale flows can be used to reconstruct the mass-loss history and thus, by inference, mass-accretion history of the source (Reipurth & Bally, 2001).

The spectra of HH objects are dominated by line emission, allowing us to broadly categorise them of being of low or high excitation. High excitation objects have spectra dominated by strong [OIII] λ 5007 emission but weak [SII] $\lambda\lambda$ 6716,6731 and [OI] $\lambda\lambda$ 6300,6363 lines. The reverse is true of low-excitation shocks (Edwards et al.,

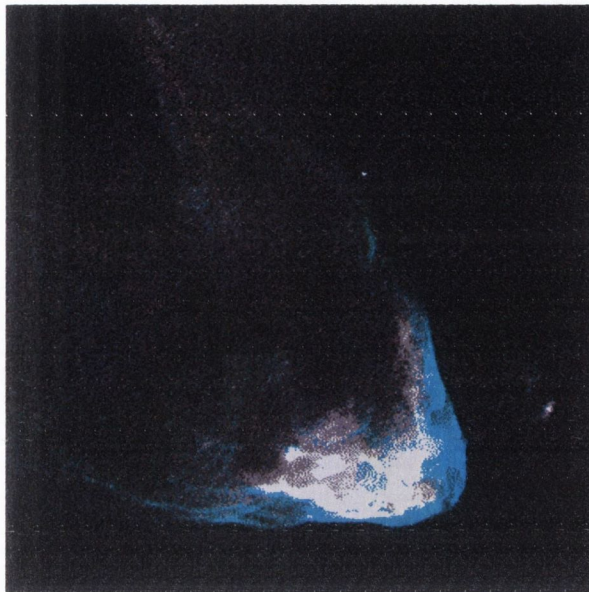


Figure 1.7: The HH34S bow shock and Mach disk as seen by the Hubble Space Telescope. The high excitation bow-shock front is strong in $H\alpha$ (green) and the cooling zone behind radiates brightly in $[SII]$ (red). The mach disk is also detected behind the bow-shock in $[SII]$.

1993). Emission line ratios, line profiles and indeed line intensities, are strongly influenced by the structure of the shocks causing the emission, hence a study of the emission lines of HH objects allowed a number of different shock models to be considered. Emission spectra were initially compared with plane-parallel models (Dopita, 1978) however these models could not simultaneously explain the detection of low excitation lines like $[SII]\lambda\lambda 6716, 6731$ and $[OI]\lambda\lambda 6300, 6363$ along with highly ionised species like $[OIII]\lambda 5007$. It was soon realised that bow-shock models best accounted for the observed spectra of many HH objects (Reipurth & Bally, 2001). Although the classification of HH objects is based purely on optical emission, cooling zones of shocks are also seen in the near-infrared and the ultraviolet (Davis et al., 1994, 2000a; Böhm, 1983; Cameron & Liseau, 1990). Molecular hydrogen is the main infrared coolant in shocks however, they also emit several strong $[FeII]$ lines such as the line at $1.644\mu m$.

The Physics of Herbig Haro Shocks

As the collimated protostellar jet interacts with the undisturbed ambient medium, it generates what is known as a “working surface” (Raga & Cabrit, 1993) that

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the observer then sees as an HH object. The most violent interaction occurs at the initial point of contact between the jet and the ambient medium resulting in a terminal working surface, which is often bow-shaped (for example HH 34S, Figure 1.7. Internal working surfaces trace milder internal collisions within the outflow itself. Each HH object or knot represents a major event of mass ejection and it is therefore likely that these internal shocks occur when fast moving gas from a fresh ejection episode catches up with slower moving material ejected earlier (Raga et al., 1990). Hence the archetypal HH jet as mentioned above is traced by a series of HH objects. This is the exact morphology of the HH 34 jet as imaged in [SII] and H α in Figure 1.8. Indeed several of the knots in this flow appear to be bow-shaped, consistent with the idea that they are internal working surfaces.

Each working surface whether internal or terminal is actually composed of two shocks. A forward shock (normally a bow) and a Mach Disk or reverse shock. The forward shock represents the initial region of collision, where the ambient or slower moving material ahead of the shock is accelerated outwards. However the jet (or faster moving material) is slowed by this interaction resulting in a reverse shock. A contact discontinuity separates the post-shock cooling zones of the forward and reverse shocks. Across the contact discontinuity temperature and density vary but pressure remains constant. Hence there is no flow.

Consider the jet moving with velocity $\mathbf{V}$ across the Mach disk. Refer to Figure 1.9. $\mathbf{V}$ is greater than the sound speed (C_s) in the preshock gas hence the postshock material in effect cannot communicate via sound waves to the material in the jet that it is about to collide with the ambient medium. Thus the preshock material suddenly undergoes a jump in pressure, density and temperature known as a J-shock, when it hits the ambient medium. The Rankine-Hugoniot jump conditions are used to derive the change in the density and velocity of the preshock material as it leaves the shock front (Draine & McKee, 1993). For $\mathbf{V} \gg C_s$, that is for a strong shock, the Mach number M , given by $M = \mathbf{V}/C_s$ is high and after crossing the shock $\rho \rightarrow 4\rho$ and $\mathbf{V} \rightarrow \mathbf{V}/4$, in the shock frame. Figure 1.9 is an illustration of the structure of the working surface in the shock frame. $\mathbf{V} = \mathbf{V}_{jet} - \mathbf{V}_{bow}$ as it approaches the Mach disk and $\mathbf{V} = \frac{\mathbf{V}_{jet} - \mathbf{V}_{bow}}{4}$ as it leaves it. The ambient medium, in the shock frame, moves towards the bow shock with a velocity $\mathbf{V}_{bow}$ and when it crosses the bow-shock front this decreases to $\mathbf{V}_{bow}/4$.

Radiative cooling then occurs, causing the density in both post shock zones to increase even further, in order to maintain pressure. Material then flows away from

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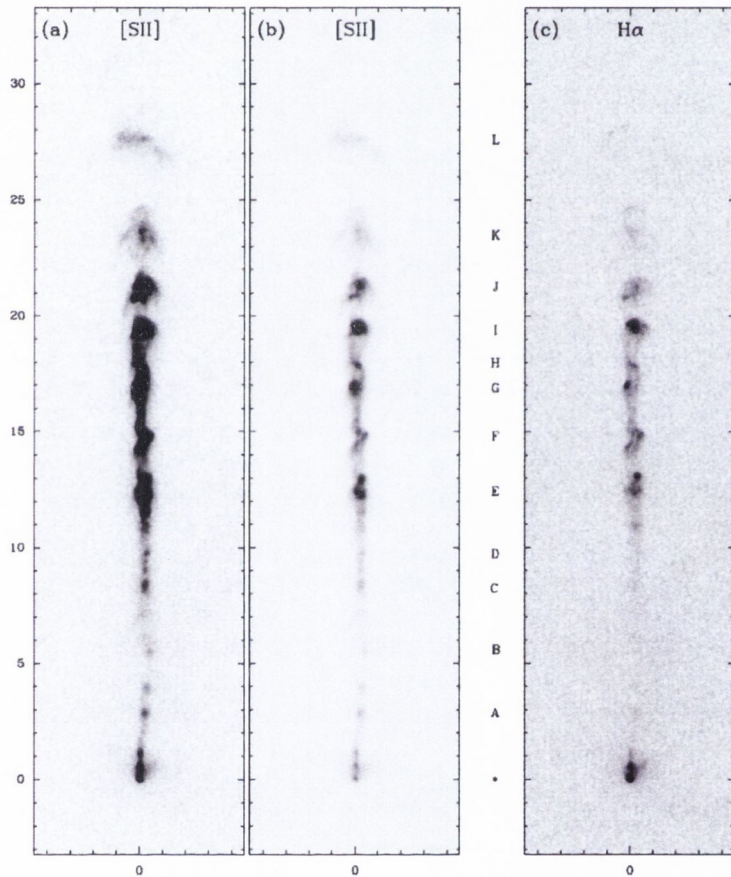


Figure 1.8: HH 34 jet in $[SII]\lambda\lambda 6716, 6731$ and $H\alpha$, based on Wide Field Planetary Camera 2 (WFPC2) images from the HST. The knots or internal working surfaces within the flow are labelled A to L. Several of the knots appear to be bow shaped especially Knot L. This figure is taken from Reipurth et al. (2002) and (a) and (b) are two different intensity cuts of the $[SII]\lambda\lambda 6716, 6731$ emission.

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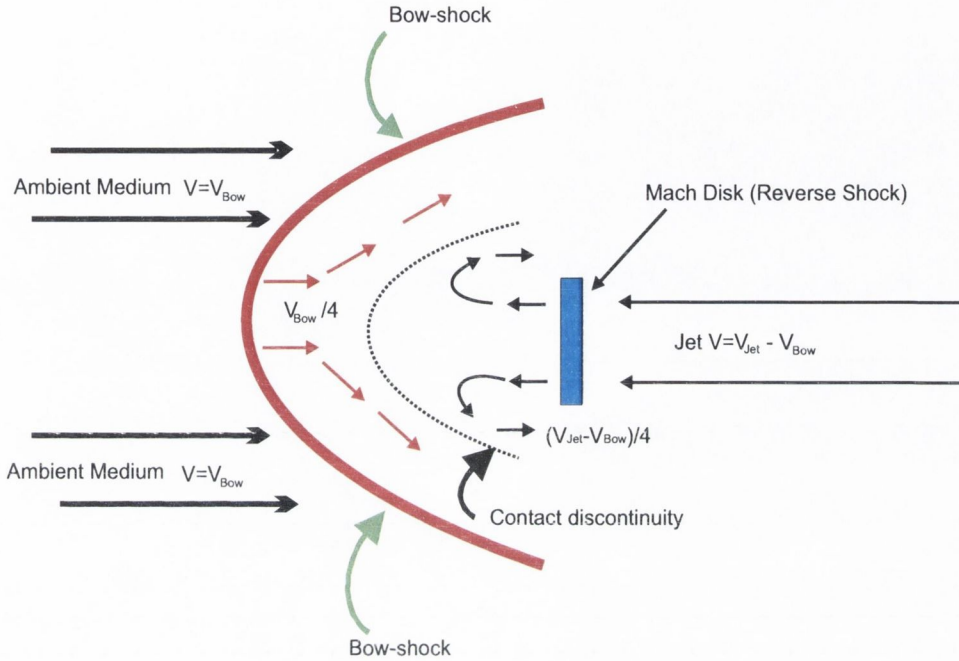


Figure 1.9: Internal structure of a terminal working surface. Note that velocities marked are in the shock frame of reference. See section 1.2.1 for an explanation of this structure.

the head as indicated by the arrows in Figure 1.9. Radiative shocks consist of a very thin layer of material at the shock front where the gas is ionised and an extended cooling zone. Most of the radiation that is observed as a HH object originates from this cooling zone. The cooling zone tends to be bright in forbidden lines of metals and recombinations lines of hydrogen whereas strong Balmer line emission is associated with the shock front. Again this is beautifully illustrated by the HH 34S bow-shock. In Figure 1.7 the bow-shock and Mach disk are both observed. The leading edge of the high excitation bow-shock is strong in $H\alpha$ (green) whereas its post-shock cooling zone and Mach disk are strong in $[\text{SII}]$ (red).

Giant Herbig-Haro Flows

Giant Herbig-Haro flows are parsec-scale length, bipolar outflows, made up of strings of HH objects (Ray, 1987; Devine, 1997). Initially these large flows were largely thought to be driven by luminous YSOs that were relatively young and still deeply embedded in their parent clouds (Poetzel et al., 1989). It was quickly realised that such giant flows could also be powered by low mass embedded (Class I) sources.

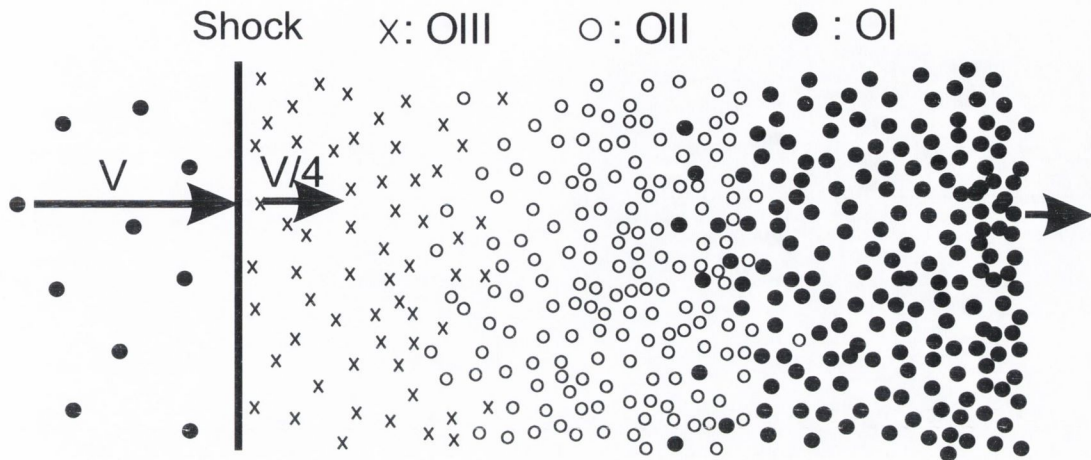


Figure 1.10: The structure of a radiative shock (in the frame of reference of the shock) taken from Hartigan et al. (2000). Material enters the shock front at the left with a velocity V and is slowed by a factor of 4 after crossing the shock. The density jumps by a factor of 4 at the shock and increases gradually as the gas cools and slows. As an example cooling zones of oxygen are depicted by the crosses, circles and dots. This illustrates how emission from different species dominates at different distances from the shock front.

One of the first parsec-scale HH flows discovered to be driven by a low mass star is associated with HH1/2. It was originally thought to be 0.4 pc in length however two large bow shock shaped HH objects HH 401 and HH 402 were observed by Ogura (1995). They are symmetrically positioned about the HH 1/2 source and their inclusion as part of the original flow increases its length to 5.9 pc. Dozens of giant HH flows have now been studied the largest of which are almost 12 pc. McGroarty et al. (2004a) and McGroarty & Ray (2004b) built on the studies of large-scale outflows from embedded low and intermediate mass sources by demonstrating that the more evolved Classical T Tauri stars (CTTS) and their intermediate mass counterparts, the Herbig Ae/Be stars, also drive outflows that reach parsec scales.

These immense optical flows have many interesting features. Firstly as the ages of these flows ($\sim 10^4$ yrs) are a significant fraction of the accretion ages of their sources, they are essentially a fossil record of the evolution of their parent star. Studies of the proper motions, radial velocities and excitation of individual HH objects within the outflow allows us to reconstruct the mass-ejection (and thus mass-accretion) history of the central YSO. Also, the distribution of the individual shocks provides clues relating to variations in the flow velocity over time, or the symmetry

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of the blue and red-shifted lobes offers information on source motion and disk orientation changes. These changes may be signatures of dynamical interactions in multiple star systems or clusters (Reipurth & Bally, 2001). Secondly, as stated in section 1.1, large HH outflows may be an important source of turbulence in molecular clouds. This is likely to be most prominent in the initial stages of the outflow, when large amounts of gas are entrained by the outflow and thus expelled from the parent core, creating large wind-swept cavities in the surrounding cloud (Reipurth et al., 1998; Bally et al., 1999).

1.2.2 Molecular Outflows

Molecular outflows are another large-scale expression of the outflow phenomenon and again were one of the first observational manifestations of the mass expulsion stage of the star formation process. While giant HH flows are optically visible and composed of many HH objects, each group representing different episodes of mass ejection, molecular outflows begin when the powerful bipolar jets accelerate and drive outwards the molecular gas in the vicinity of their parent star. While it is accepted that they are powered by the primary jet from the protostar the exact way in which the jet interacts with the molecular material is still uncertain (Cabrit et al., 1997). Again these massive flows are an important diagnostic of the jet that generated them, including how energetic it is, its velocity and collimation, and how it varies in velocity and direction with time. They also impact on their parent molecular clouds, not only by producing turbulence but by influencing its chemistry.

Molecular outflows are primarily detected in the CO molecule and thus millimeter observations have dominated the search for them. To date over 250 molecular flows are known to exist (Fukui et al., 1993; Bachiller, 1996). High velocity CO emission is associated with the majority of HH outflows and some parsec-scale outflows were first recognised through the detection of their CO emission (Ray, 1987; Bence et al., 1996). In most giant flows the optical component is an order of magnitude larger than the associated CO emission however there are some cases where the molecular component extends beyond and reflects the dynamics of its underlying optical counterpart (Reipurth & Bally, 2001). For example Yu et al. (1999) discuss the giant HH flow powered by IRS 1 in Barnard 5. Here the optical flow is co-spatial with the molecular emission. It is possible, however, that selection effects

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are involved here. The strongest CO emission is seen to coincide with the brightest HH objects, and bow-shock shaped regions of CO emission are observed beyond the HH objects found furthest from the driving source. Figure 1.11 shows contour maps of the high and low velocity (bottom and top respectively) velocity CO(J=2-1) outflow surrounding the HH 211 outflow (seen in the infrared). Also shown is the $2.12\mu\text{m}$ H₂ emission. This map is taken from Reipurth & Bally (2001). Note how the high velocity CO emission appears much more collimated than the low velocity emission, suggesting a decrease in outflow velocity with increasing distance from the central outflow axis.

1.2.3 Outflow Activity in the Jet Launch Region

Many studies and indeed spectacular images, of large-scale bipolar outflows from YSOs of varying mass and in various stages of evolution now exist. While it is true that much new and important information has been gleaned from these studies, observations of the small-scale stellar jets which are in a way the catalysts of these large-scale manifestations of outflow activity are also vital. If a thorough understanding of how jets are launched, become collimated and indeed interact with the circumstellar disks of their drivers is to be gained, observations of jets on scales comparable to the central engine must be provided. For the nearest star-forming regions these scales translate to $\sim 1''$ and imaging of these “micro-jets” (Reipurth & Bally, 2001) is challenging due to contamination by stellar radiation. Long-slit spectroscopy can solve this problem as it allows one to examine the structure and kinematics of the jets on the smallest spatial scales available, while minimising any contrast problem with the source. Using intermediate dispersion spectroscopy it is possible to easily remove the contribution from the source, revealing in many cases the stellar jet down to scales of $1''$.

Figure 1.12 compares observations of the DG Tau micro-jet obtained in various ways. Part A is a broadband H α image taken by Mundt & Fried (1983). While the jet is resolved from the source it is only separated on a scale of $\sim 5''$. The image is corrupted by light from the star and no information can be obtained on a scale of $\sim 1''$. The DG Tau micro-jet is separated from its source in the continuum subtracted long-slit spectrum presented in part B. Only the [SII] $\lambda 6731$ ELR is shown. Two knots at a distance of $\sim 12''$ are clearly resolved as well as Knot A at the source. This spectrum was taken on the INT using the IDS. It forms part of the results

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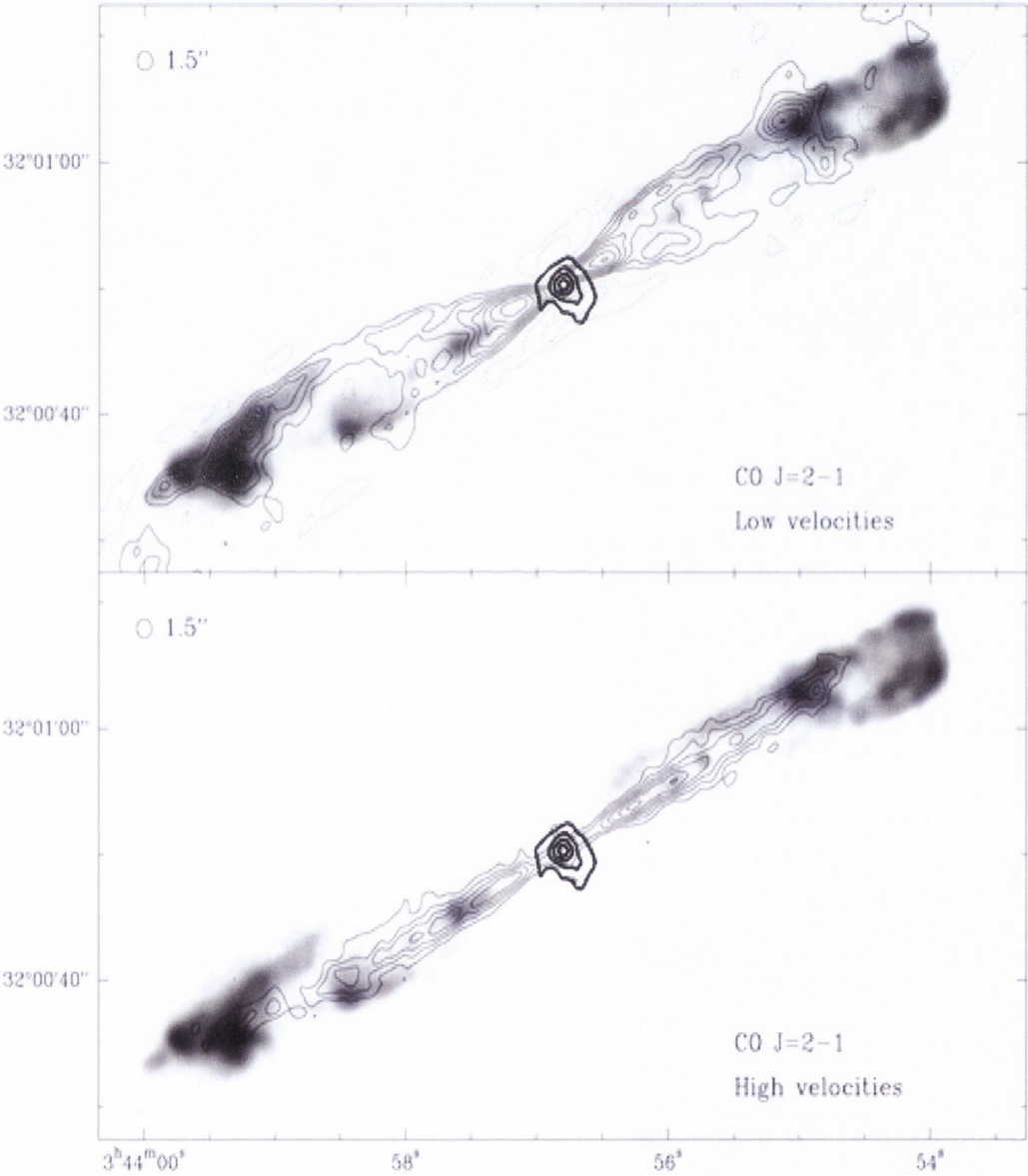


Figure 1.11: The high-velocity CO($J = 2-1$) outflows surrounding the HH 211 infrared jet. The inner faster flow is more collimated than the outer slower flow. The lobes terminate in infrared molecular hydrogen shocks. The driving source is surrounded by cold dust seen in 1.3 mm continuum emission (Reipurth & Bally, 2001; Gueth & Guilloteau, 1999).

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discussed in Chapter 4. The spatial sampling of this observation is $\sim 0''.2$ per pixel. Using spectro-astrometry (see Chapter 2) spatial information on Knot A is recovered on scales much less than $1''$ as is evident from Figure 1.12 part C.

Spectroscopy was used very early on in the study of protostars (Herbig, 1962). It was often the case that the strong Balmer lines ($H\alpha$ and $H\beta$) seen in the spectra of the majority of YSOs, showed deep blue-shifted absorption features or P-Cygni profiles. This absorption feature occurs because light from the star's continuum or a line wing is absorbed by out-flowing material from the YSO. Hence the detection of P-Cygni profiles was another early indication that YSOs undergo mass loss (Reipurth et al., 1996). In section 1.2.1 I discussed how the radiative nature of HH objects means that they are strong in forbidden emission lines (FELs) like $[OI]\lambda\lambda 6300, 6363$, $[SII]\lambda\lambda 6716, 6731$ or $[FeII] 1.644\mu m$. FELs are strong tracers of outflow activity from YSOs and I cannot emphasise enough the contributions that studies of the FEL regions (FELRs) of YSOs has made to our knowledge of jets in the region closest to where they are launched (Eislöffel et al., 2000).

Solf & Böhm (1993) published some of the first FEL spectroscopic observations of CTTSs. In many cases early forms of spectro-astrometry were used to accurately map the FELRs of the sources (Hirth, Mundt, & Solf, 1997). Spectro-astrometry is the key to the results presented in this thesis. Using this technique I was able to uncover much new and important information on the ELRs of many different types of YSOs from Classical T Tauri stars to Herbig Ae/Be stars and even young BDs. In Chapter 2 I give an introduction to this technique and in particular I outline how it has been used previous to this thesis to study FELRs. The most notable features that very early observations of FELs revealed is that the FELs of CTTSs are in most cases blue-shifted and often double-peaked (Cohen & Kuhl, 1979; Jankovics et al., 1983). The two detected components were easily separated into a low and high velocity component, or a LVC and a HVC. In a study of 38 T Tauri stars by Hirth, Mundt, & Solf (1997), 50% of the T Tauri stars in a sample of 33 objects with high signal to noise $[OI]\lambda 6300$ line profiles showed a double peaked profile. Typically the LVC is at $\leq 50 \text{ km s}^{-1}$ and the HVC is at $\geq 100 \text{ km s}^{-1}$ with respect to the systemic velocity of the star. In Figure 1.13 some examples of multi-component FEL profiles from a CTTS, a Class I low mass object and a Herbig Ae/Be star are shown. The blue-shifted nature of the lines arises from the circumstellar disk of the source which obscures the red-shifted flow (Edwards et al., 1993). The multiple components are easily explained by the disk-wind model of Kwan (1997) which I

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shall now outline. Appendix A is a thorough discussion of a number of important properties of FEL profiles, including critical density and the influence of opening angle and inclination to the line of sight, on the shape of the observed profiles.

The Disk-wind Model

Early attempts at explaining the multi-component FELs of CTTSs centred on wide angle winds viewed at different projection angles (Edwards et al., 1987). Such attempts however were not very successful (see Appendix A). Kwan & Tademaru (1988) initially proposed the two-component disk-wind model. They suggested that the HVC represented a fast well collimated jet and the LVC a much slower less focussed wind from the circumstellar disk. Kwan (1997) use the ratio of the [OI] λ 5577 and [OI] λ 6300 lines to infer physical conditions in the LVC and found the electron densities $n_e \sim 10^7 \text{ cm}^{-3}$, and temperatures $T \sim 8000\text{K}$.

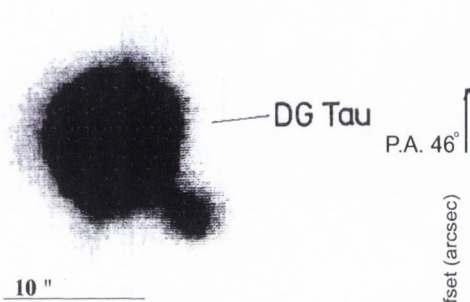
Observational evidence confirming that the LVC and HVC were physically distinct regions, rather than two projections of the same underlying flow are based on their different FEL properties. For example in [OI] λ 5577 the LVC is mostly seen whereas in [NII] λ 6583 the HVC dominates (Hamann, 1994; Hartigan et al., 1995; Hirth, Mundt, & Solf, 1997). Hirth, Mundt, & Solf (1997) also examined the spatial properties of the FELRs and clearly showed that the high velocity emission is displaced further from the source than low velocity emission, again attesting to the separate origins of the two components.

Launching Jets: Two Different Models

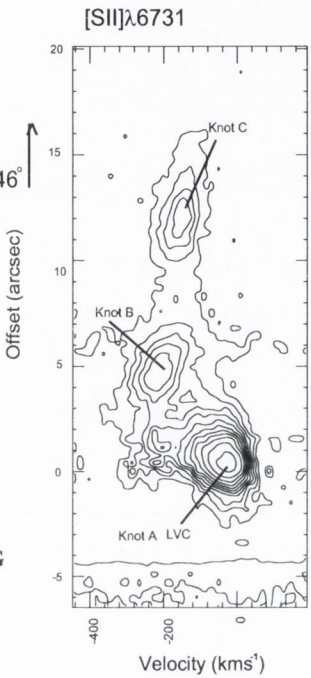
It is now generally agreed that outflows from young stars are launched centrifugally along magnetic field lines, although the precise mechanism is still hotly debated (Königl & Pudritz, 2000; Shu et al., 2000). The centrifugal force originates due to the rotation of the circumstellar accretion disk. Hence outflows are ultimately powered by the infall of material although rotation and magnetic fields play a crucial role in the whole process. Indeed it is possible that outflows are the lynchpin of the star formation process, removing angular momentum from the star-disk system and thus preventing the star from rotating at its break-up velocity. Evidence that energetic winds are powered by accretion comes in many forms. For example invariably outflows come from sources surrounded by Solar System sized accretion disks. Moreover there is a strong correlation between mass outflow

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A) $H\alpha$ image of the DG Tau jet at the source
taken from Mundt & Fried (1983)



B) Long-slit spectrum of the $[SII]\lambda 6731$ emission line region of the DG Tau jet. Knots A, B and C are detected.



C) Emission line profile and spectro-astrometric plot of Knot A in the DG Tau jet.

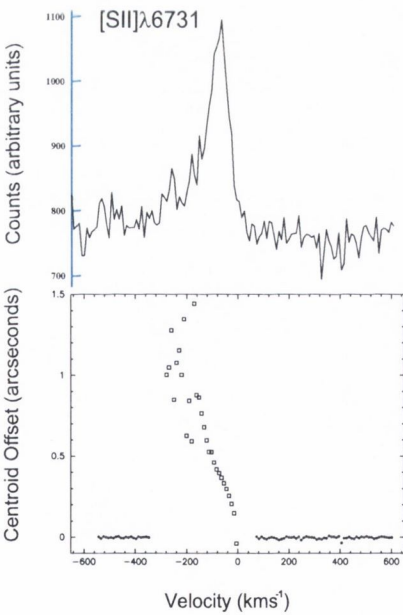


Figure 1.12: Observations aimed at resolving the small scale from DG Tau. Contamination by stellar radiation make direct imaging difficult. Observation A is a $H\alpha$ image (from Mundt & Fried, 1983) which resolves the jet but the source emission is not well differentiated and no detail is resolved. The long-slit spectrum shown in B was taken as part of the work discussed in Chapter 4. The continuum emission from the source is easily removed revealing Knot A which is part of the micro-jet. Information can be recovered on a scale of less than $1''$ using spectro-astrometry (part C).

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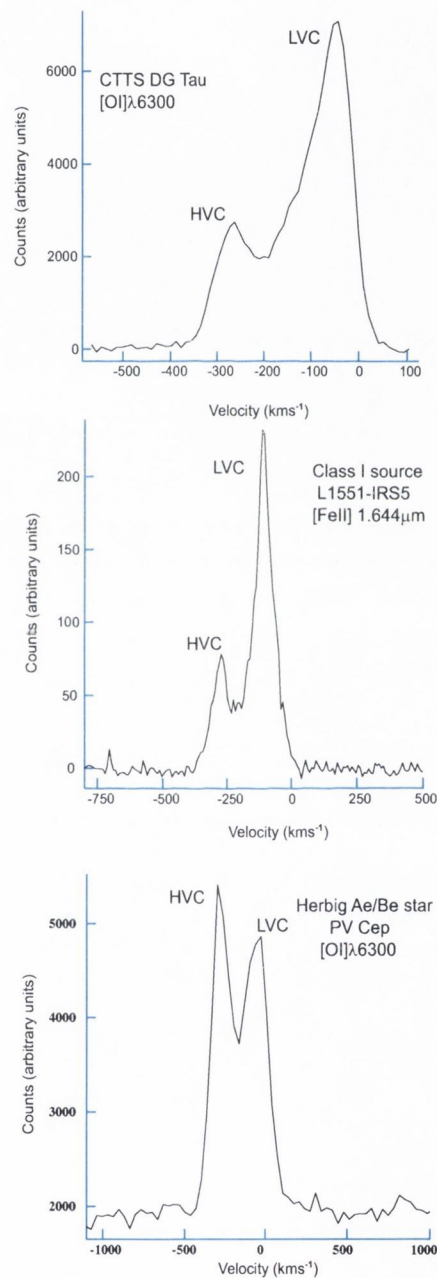


Figure 1.13: Multi-component FEL profiles of a CTTS, a Class I low mass star and a Herbig Ae/Be star. These figures represent some of the results discussed in this thesis. The LVC and HVC are clearly separated in each case.

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and mass accretion rates. This is to be expected if infall provides the energy to launch the jets (Edwards et al., 1993). Overall mass loss carries away $\sim 10\%$ of the potential energy released by accretion (Hartigan et al., 1995). While models agree on the basics of how jets are launched it is from where precisely they are launched that causes the most debate. The two most widely favoured models are the X-wind model (Shu et al., 2000) and the magneto-centrifugally driven disk-wind model (Königl & Pudritz, 2000).

The X-wind model suggests that material is accelerated outwards from the zone where the stellar magnetosphere co-rotates with the disk (see Figure 1.14). This point of interaction between the protostar and the disk is called the *X-point*, although properly speaking it is a circular zone lying typically a few stellar radii from the source. Beyond the X-point the magnetic field lines have an open, rather than a closed topology. Shu et al. (2000) outline four separate observational studies that strongly support the X-wind idea. Briefly, rapidly rotating disks are observed to extend almost to the surface of protostars of mass $\sim 1M_{\odot}$, protostars are magnetised to the extent needed to truncate the disks at a value of R_X compatible with low stellar rotation rates, accretion onto the protostar occurs along magnetic field lines (the *magnetospheric* accretion model) and lastly the flow of material onto the protostar (“funnel flow”) is observed to have a geometry and phase relationship consistent with the predictions of the X-wind model.

In the disk-wind model winds are launched from the circumstellar disk only, along the open magnetic field lines that emanate from the disk. According to this model the highest velocity material in the jet is launched at a distance of $\sim 0.1\text{AU}$ from the protostar. See Figure 1.15 for an illustration of this model. There are several variations on this theme, as discussed by Königl & Pudritz (2000). Königl & Pudritz (2000) claim that disk-wind models provide the most efficient way of harnessing the power of accretion to launch an outflow. However some studies claim that the magnetic fields required to satisfy these models cannot be generated in a typical accretion disk (Bachiller, 1996).

Collimation of Stellar jets

Once the wind is launched centrifugally it then, in both the X-wind and disk-wind models, has to be collimated. As the gas moves outwards along the magnetic field lines, its angular velocity is approximately constant, and so its azimuthal velocity

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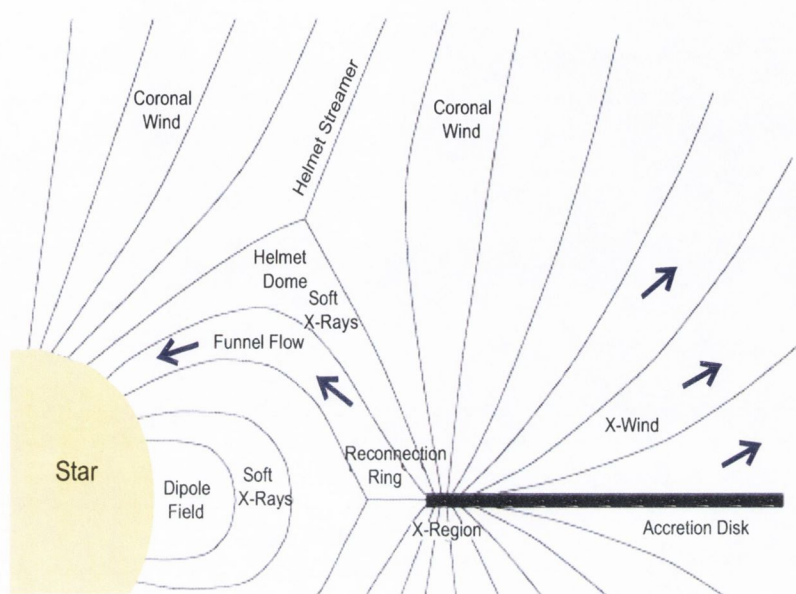


Figure 1.14: Drawing of the X-wind model for the launch of protostellar jets taken from Shu et al. (2000). The magnetic field of the star connects to the disk at the X-point. At this point the accretion disk and star are co-rotating and a strong wind is launched outwards along the open magnetic field lines.

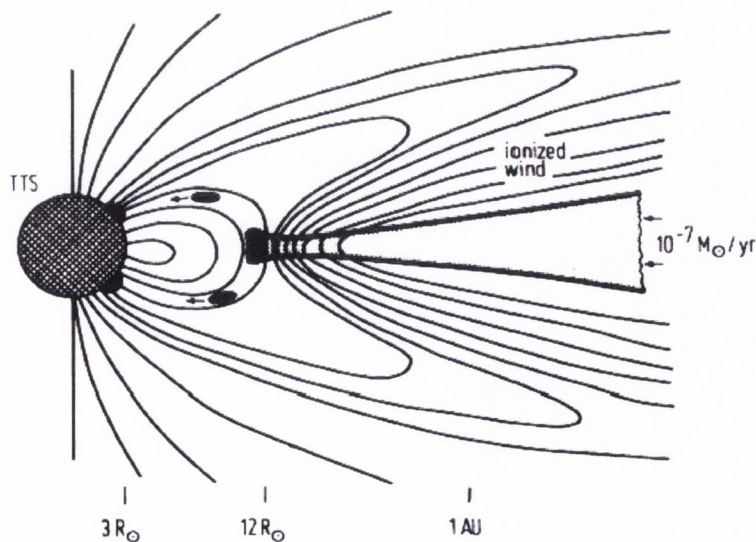


Figure 1.15: A depiction of the disk-wind model, used to explain how a protostellar jet is launched, taken from Camenzind (1990). A strong wind is launched along the open field lines emanating from the accretion disk.

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V_ϕ increases. However once V_ϕ reaches a large enough value such that the magnetic tension

$$\frac{B^2}{\mu_o r_A} \quad (1.1)$$

balances the centrifugal force per unit mass

$$\frac{\rho V_\phi^2}{r_A} \quad (1.2)$$

the field lines are distorted by the inertia of the gas. Here B is the magnetic field, μ_o the permeability of free space, r_A the so-called Alfvén radius and ρ the gas density. At the Alfvén radius then, the azimuthal velocity is the Alfvén speed and the magnetic field takes on an increasingly toroidal topology. Finally the “hoop stresses” generated by this field focus the wind into a jet along the outflow axis (Königl & Pudritz, 2000; Shu et al., 2000).

From an observational perspective this initial “collimation zone” should be relatively close to the source (at most within a few AU) and therefore difficult to probe. There is however evidence that some re-collimation of jets may occur on larger scales (i.e. a few hundred AU), presumably due to external thermal or magnetic pressure. In these regions jet collimation can be studied by measuring the width of the jet (starting as close to the central engine as possible) as a function of distance from its source. A simple approach is to define two opening angles to constrain the collimation properties of jets, an initial opening angle α_i which is the average measurable opening angle at the minimal distance from the source and α_a , which is the average value defined by the most distant knots (Eislöffel et al., 2000). Ground based studies (Mundt et al., 1991; Raga et al., 1991) and HST observations (Ray et al., 1996) all confirmed that for the majority of cases α_i is much larger than α_a . Typical values of α_a ranged from approximately 0° to 3° and $\alpha_i \geq 3\alpha_a$ was applicable to the majority of sources. These studies proved that jets may well be re-collimated on scales of roughly 1000AU into narrow highly concentrated flows (Raga et al., 1991).

Rotation of Stellar jets

An important consequence of the models discussed above is that they predict rotation in the jet at its base. Hence they also allow for the removal of angular momentum from the star-disk system, thus braking the rotation of the disk. The

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question as to how a protostar sheds its angular momentum, thus enabling it to accrete an indefinite amount of mass, was not satisfactorily answered until the discovery of the first outflows (Shu et al., 1993). However, until recently observations failed to confirm the rotation of stellar jets

Davis et al. (2000b) found hints of rotation in the HH 212 outflow at large distances from the source (10^4). On these scales it is not possible to confirm if rotation is caused by the interaction of the jet with the ambient medium or if it is a residual of the acceleration mechanism. To truly test the above prediction, one must search for signatures of rotation on scales comparable to the size of the central engine (less than 100 AU from the star). Such scales have been successfully probed using the Space Telescope Imaging Spectrograph (STIS) on the HST and observations of several sources have confirmed that jets are rotating at distances close to their point of origin (Bacciotti, 2004). For example for DG Tau and RW Aur (Bacciotti et al 2002, Coffey et al 2004) the STIS 0".1 slit was stepped across the flow at intervals of 0".07, thus building up 3D observations of the jets very close to the disk. Systematic differences in the radial velocity were found for each pair of slits displaced symmetrically from the jet axis, confirming rotation. Figure 1.16 illustrates how rotation was observed in the DG Tau jet.

1.3 Outflow Activity Across the Mass Spectrum. From Sub-stellar Brown Dwarfs to Intermediate Mass Herbig Ae/Be Stars

The initial mass function (IMF) describes the distribution of stellar masses within a star-forming region or cluster. This function, defines the relative numbers of sub-stellar ($< 0.1M_{\odot}$), low ($0.1M_{\odot}\sim 2M_{\odot}$), intermediate ($2M_{\odot}\sim 10M_{\odot}$) and high mass stars ($> 10M_{\odot}$). Meyer et al. (2000) define the IMF as the number of stars per unit logarithmic mass interval and approximate the mass function using a power law of the form

$$\Gamma = d\log F(\log M_{\star})/d\log M_{\star} \quad (1.3)$$

Historically the IMF was approximated with the Salpeter function (Salpeter, 1955) and in the above notation the slope of this function is $\Gamma = -1.35$. Figure 1.17 shows the IMF for field stars in the solar neighbourhood, taken from Meyer et al. (2000)

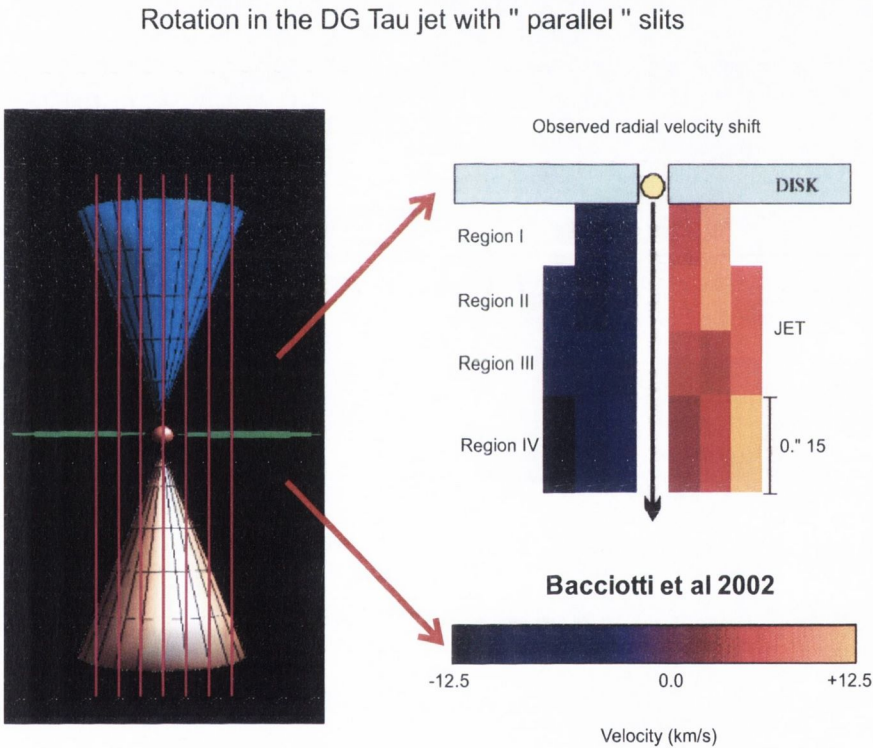


Figure 1.16: Rotation in the DG Tau jet, taken from Bacciotti et al. (2002). The Doppler velocity shifts in the line profiles observed with HST/STIS parallel stepped slits give rise to a 2D spin map in the blue lobe of the DG Tau jet.

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(results are taken from a variety of studies). In general the Salpeter function holds for low to intermediate mass stars ($1M_{\odot}$ to $10M_{\odot}$) but below $1M_{\odot}$, this function fails (Kroupa et al., 1993; Kroupa, 2000).

Although the IMF is essentially similar from one star formation region to another, differentiation is seen within individual regions. For example regions of low mass star formation may cluster together. Meyer et al. (2000) published a table of the ratios of intermediate mass to low mass stars for 9 of the closest star forming regions. Overall values range from 0.07 for the OMC-2 cloud in Orion to 0.45 for BD+40° 4124. In general the mass that forms stars can be divided as follows. Approximately 75% forms low to intermediate mass stars, 20% massive stars and 5% sub-stellar objects like BDs (Larson, 1999). When examining outflows from young stars, clear observational selection effects will occur depending on the relative number of sources.

A substantial amount of knowledge has been built up in the last two decades on bipolar outflows. Most of this comes from studies of low mass YSOs, with the bias towards this group of simply reflecting the fact that they are statistically more numerous and nearer than for example high mass stars. While much is known about low mass stars on large scales, studies of the central engines of protostars have tended to concentrate on just one subsection of this group, the CTTSs (Class II). CTTSs are low mass YSOs that have driven off much of their circumstellar gas and dust, hence they are optically visible. They are still actively accreting material and drive strong jets (Edwards et al., 1993), making them excellent candidates for any project which aims to observe jets at the central engine or jet launch region. The jet launch region of more embedded, less evolved low mass sources (Class 0 or Class I) is only observed in the near-infrared. In comparison to techniques for studying the optical spectra of YSOs near-infrared spectroscopic techniques have only been developed relatively recently thus embedded low mass YSOs were traditionally more difficult to observe explaining why less is known about their central engines.

Turning to stars of higher mass the intermediate mass Herbig Ae/Be stars, are rarer than low mass protostars (as explained above) hence they have been observed less often in comparison. They form in a similar manner to a typical low mass star however and drive outflows which are scaled up versions of low mass flows (Mundt & Ray, 1994). The subject of massive star formation is a relatively young field of study and is beyond the scope of the thesis. However it is known that massive stars form in a wholly different manner from low to intermediate mass stars (Bonnell et

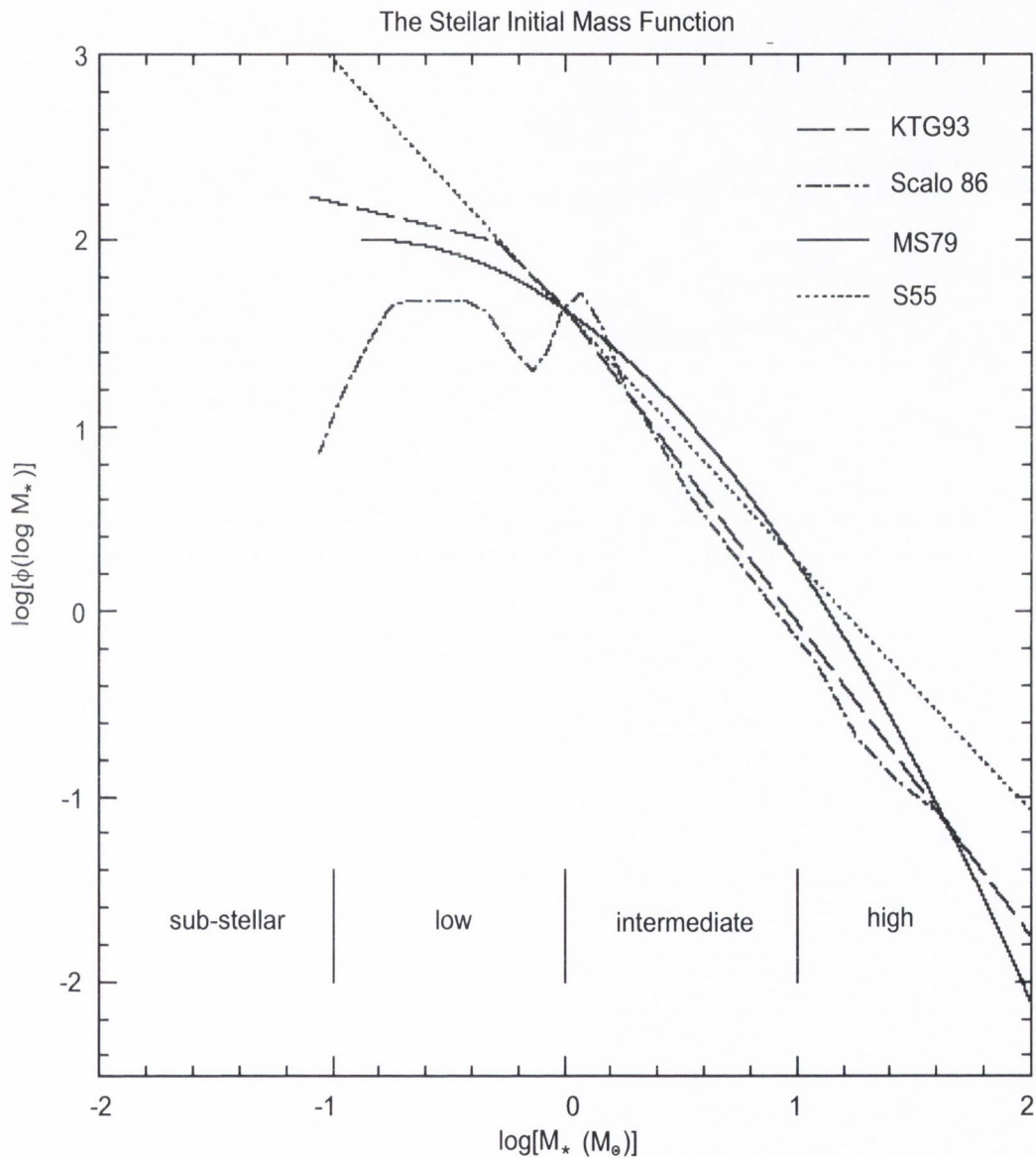


Figure 1.17: Initial mass function for field stars in the solar neighbourhood taken from a variety of recent studies: KTG93 (Kroupa et al., 1993), Scalo 86 (Scalo, 1986), MS79 (Miller & Scalo, 1979), S55 (Salpeter, 1955). These results have been normalised at $1M_\odot$. The upper end of the IMF ($>5M_\odot$) is best represented by a power law similar to that of Salpeter (1955), whereas the low mass end ($<1M_\odot$) is flatter (Kroupa et al., 1993). This figure is taken from Meyer et al. (2000).

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al., 1998) and that they drive outflows (Davis et al., 2004). In the case of sub-stellar YSOs like the Brown Dwarfs (BDs), some evidence does exist (apart from results presented in Chapter 6) to suggest that they are associated with outflows, yet little consideration has been given to this question so far and no images of BD flows have yet been taken.

From the above discussion, it is now clear that the way in which the properties of outflows from YSOs especially with regards to the central engine, vary with evolutionary stage and mass is not satisfactorily known. Hence a clear gap in our knowledge of outflow activity exists. Part of the aim of this thesis is to address this unbalance which is done by applying the spectro-astrometric technique adopted in this study to the spectra of BDs, Class I low mass sources, CTTSs and Herbig Ae/Be stars. As such this section is an introduction to each of these different types of YSOs with particular attention paid to describing how these protostars of varying mass are classified and the general characteristics of their outflows.

1.3.1 Low mass sources

Low mass protostars have masses comparable to that of the Sun ($M_{\star} \leq 2M_{\odot}$) and will eventually become solar-like main sequence stars. They are divided into four different classes Class 0 to Class III based on their near-infrared to mid-infrared spectral energy distributions (SEDs). As a young low mass star evolves the distribution of its circumstellar material changes due to accretion and the action of the bipolar outflow it drives. The radiation from the star is absorbed by the dust surrounding it and re-emitted at longer wavelengths, hence the shape of a stars SED is a direct probe of the distribution of its circumstellar material. In effect each class can be considered to be a reflection of the stage of evolution of a low mass YSO. The SED of a typical YSO is modelled as a blackbody along with the infrared/millimetre contribution from the circumstellar dust and gas.

This classification scheme was first proposed by Lada (1987) and it was based on observations of near-infrared sources in ρ -Ophiuchi obtained by Lada & Wilking (1984). Figure 1.18 outlines how the SEDs of low mass sources vary as they evolve towards the main sequence. In general it is clear that the infrared excess tells a lot about the source. Class 0 sources are deeply embedded objects which are believed to be at the beginning of the main accretion phase. They are characterised by virtually no emission shortward of $10\mu\text{m}$ and are observed mostly at sub-millimetre/radio

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Infrared/Submillimeter Young Stellar Object Classification

(Lada 1987 & Andre, Ward-Thompson, Barsony 1993)

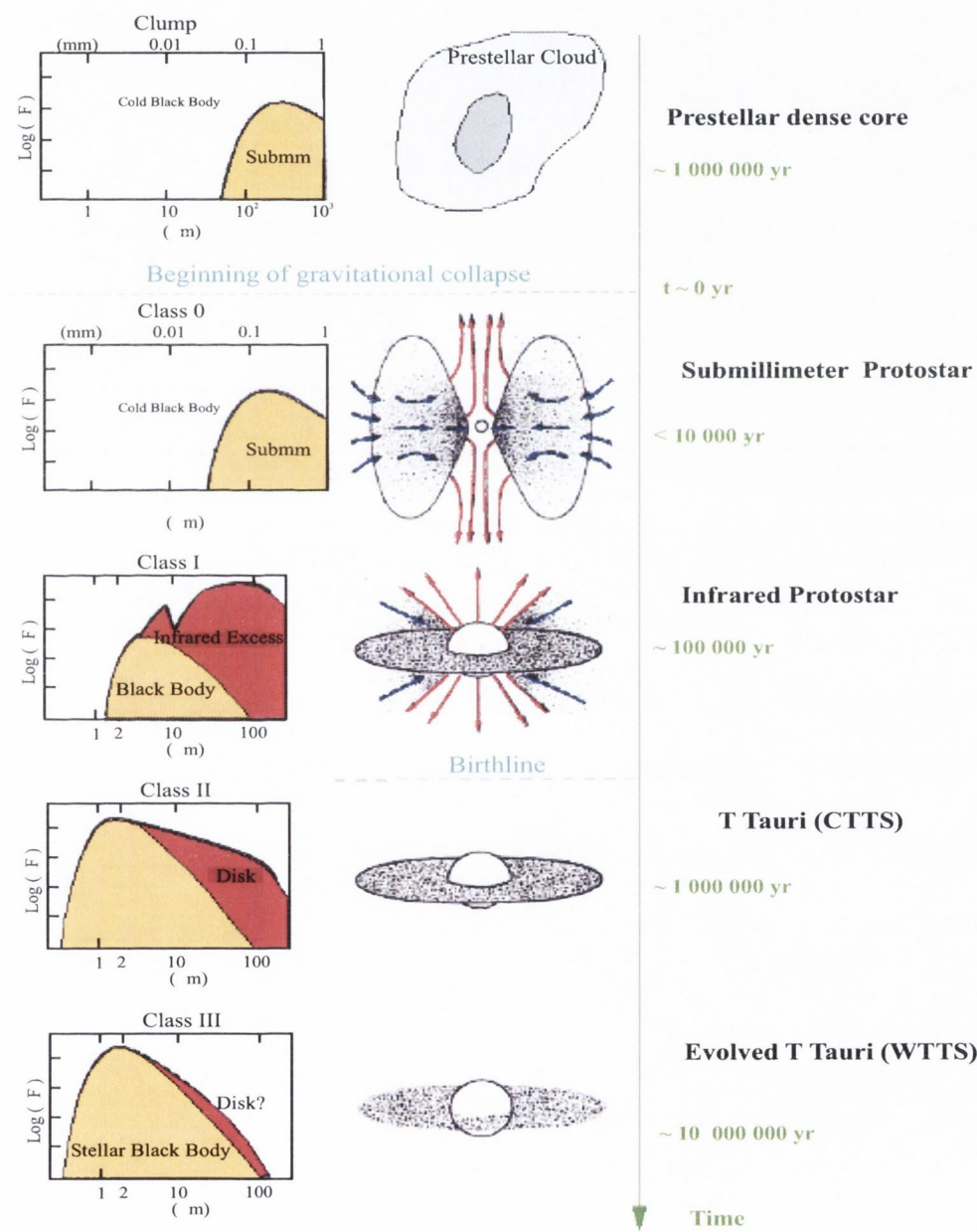


Figure 1.18: Classification of low mass YSOs

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wavelengths. They are known to drive powerful jet-like outflows. Class I sources are strongly accreting hence they have a strong infrared excess and are also associated with powerful outflows. Class II sources or CTTSs also have a strong excess, however the outflow has by this stage dispersed much of the circumstellar gas and dust and what is left is confined to the accretion disk. This is reflected in a comparison between the excess of the Class I and Class II sources. Lastly Class III have a very small excess only.

Lada (1987) make their division of the low mass stars more quantitative by basing it not on the presence or strength of an infrared excess but on the spectral index α which is defined as $\alpha = \text{dlog}(\lambda F_\lambda) / \text{dlog}(\lambda)$ (for $2\mu\text{m} \leq \lambda \leq 20\mu\text{m}$). Once the low mass source has begun to actively accrete material it can be categorised as follows using α (Lada, 1987; Barsony, 1994).

- For Class I sources $0 < \alpha \leq +3$
- For Class II sources $-2 \leq \alpha \leq 0$
- For Class III sources $-3 < \alpha \leq -2$

Since the relative amount of circumstellar matter decreases in going from Class 0 to Class III, it seems reasonable to infer that Class 0 protostars evolve to Class III pre-main sequence stars by passing through the Class I and Class II stages. Some studies suggest however that some Class I sources may evolve either directly to Class III or more rapidly through Class II than others of comparable mass (Gras-Velázquez & Ray, 2004; Gregorio-Hetem & Hetem, 2002; Walter, 1986)³. Class II and Class III low mass sources are collectively called T Tauri stars (TTs), named after the low mass protostar T Tau. Joy (1945) noted the presence of strong H α emission in the spectra of the first TTs to be discovered. Subsequently it was found that they can be separated into Classical T Tauri stars and Weak line T Tauri stars (WTTs) according to the equivalent width of their H α line. In general CTTSs have $\text{EW}(\text{H}\alpha) > 10\text{\AA}$ and WTTs have $\text{EW}(\text{H}\alpha) \leq 10\text{\AA}$. The CTTSs are the Class II low mass objects and the WTTs are the Class III objects.

Most of what is known about protostellar outflows as described in section 1.2 is relevant to the low mass sources. They drive fast (in general $V_{\text{jet}} \sim 200 \text{ km s}^{-1}$), well collimated bipolar jets for $\sim 10\%$ (10^6 yrs out of 10^7) of their pre-main sequence

³For example co-eval weak-line T Tauri stars (Class III) and Classical T Tauri stars (Class II) of identical mass may co-exist in the same cloud

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phase (from initial collapse to the end of accretion). These jets interact with their parent clouds exciting HH objects and driving out the ambient molecular gas in two large lobes. They have strong FELRs which trace outflow activity in the jet launching region and their FEL profiles are explained using the model of Kwan & Tademaru (1988). It was thought that outflows from the more evolved CTTSs were less powerful or differed greatly from Class I flows however an accurate comparison of the energetic winds of the embedded Class I sources and the CTTSs proved this to be untrue (Edwards et al., 1993). Indeed McGroarty & Ray (2004b) showed that it is not just the Class I sources but also the CTTSs that are the drivers of parsec-scale HH outflows. In Chapters 3 and 4 I present results on the outflow activity of the low mass YSOs.

1.3.2 Herbig Ae/Be stars

Herbig (1960) was the first to define the characteristics of the intermediate mass analogues of the TTSs. This group of stars, subsequently known as Herbig Ae/Be stars, were described as having (a) a spectral type of A or B with emission lines, (b) an infrared excess due to hot or cool circumstellar dust or both, (c) a luminosity class III to V (Waters & Waelkens, 1998) and (d) an association with reflection nebulae. They were also shown by Finkenzeller & Mundt (1984) to have strong $H\alpha$ emission. One of the interesting things about Herbig Ae/Be stars is that they bridge the gap between low and high mass star formation. Hence their study should help reveal how the process of star formation varies with mass.

They can be classified through their infrared SEDs (refer to Figure 1.19). Hillenbrand, Strom, Vrba, & Keene (1992) studied the SEDs of 47 Herbig Ae/Be stars and placed them into one of three groups. Group I objects all had a large infrared excess which could be modelled by assuming that this excess arose in a flat, optically thick circumstellar disk. The excess of Group I objects was characterised by a spectral slope $\lambda F_\lambda \sim \lambda^{-4/3}$. The above authors suggest that Group I Herbig Ae/Be stars are the intermediate mass analogues of the CTTSs. Group II objects had a flat or rising infrared spectrum best explained by assuming that these objects are surrounded by infalling envelopes of circumstellar material rather than flat accretion disks. For this reason they can be compared to Class I low mass protostars. The Herbig Ae/Be stars belonging to Group III were similar to the Class III low mass objects in that had only small infrared excesses. Fuente et al. (1998) propose an

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alternative scheme based on the morphology of the parent molecular cloud. Type I stars are deeply embedded, have ages of $\sim 10^5$ years and drive bipolar outflows. Type III sources are located in a cavity in the molecular cloud so have driven away all their circumstellar gas and dust. They have ages of $\sim 10^6$ years and do not have outflows. Type II are the intermediate case. They are not deeply embedded and they do not drive outflows.

Again the intermediate mass stars exhibit many if not all of the properties of outflows discussed in section 1.2. They drive strong molecular outflows, are associated with parsec-scale optical outflows (McGroarty et al., 2004a) and a number of Herbig Ae/Be sources are known to have micro-jets (Corcoran & Ray, 1998b). The properties of these jets can be considered to be scaled-up from the low mass protostars. Mundt & Ray (1994) estimate that their flows are 2-3 times faster (600 km s^{-1} to 900 km s^{-1}) than low mass flows and that mass loss rates from low mass to intermediate mass increase from 10^{-9} - $10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$ to 10^{-8} - $10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$. McGroarty & Ray (2004b) demonstrated that the degree of collimation of their jets is comparable to those from low mass sources. Less is known about their central engines, however recent studies of their FELRs have shown that while they have strong FELs multi-component FEL profiles reminiscent of the CTTSs are scarcer. In Chapter 5 I examine a number of Herbig Ae/Be stars using spectro-astrometry and I address the subject of whether their FELRs differ fundamentally from those of TTSSs.

1.3.3 Brown Dwarfs

Planets are not the sole occupants of sub-stellar part of the mass spectrum but they are accompanied by the equally elusive Brown Dwarfs (BDs). BDs are the so-called “failed stars”, that never manage to reach temperatures high enough for normal hydrogen fusion to occur. Thus they provide the missing link between stars and planets. It is the mass of such objects ($0.013\text{M}_{\odot} \leq \text{M}_{BD} \leq 0.075\text{M}_{\odot}$) which is just below the normal hydrogen burning limit and above that for deuterium, that separates them from low mass stars and planets (Basri, 2000a).

They were initially predicted by Kumar (1963) and this prediction was followed by a flurry of interest in the 1980s aimed at discovering the first BD. It was not until 1995, however, that the first confirmed detections were made (Rebolo, Zapatero-Osorio, & Martin, 1995) and the length of time it took astronomers to discover the

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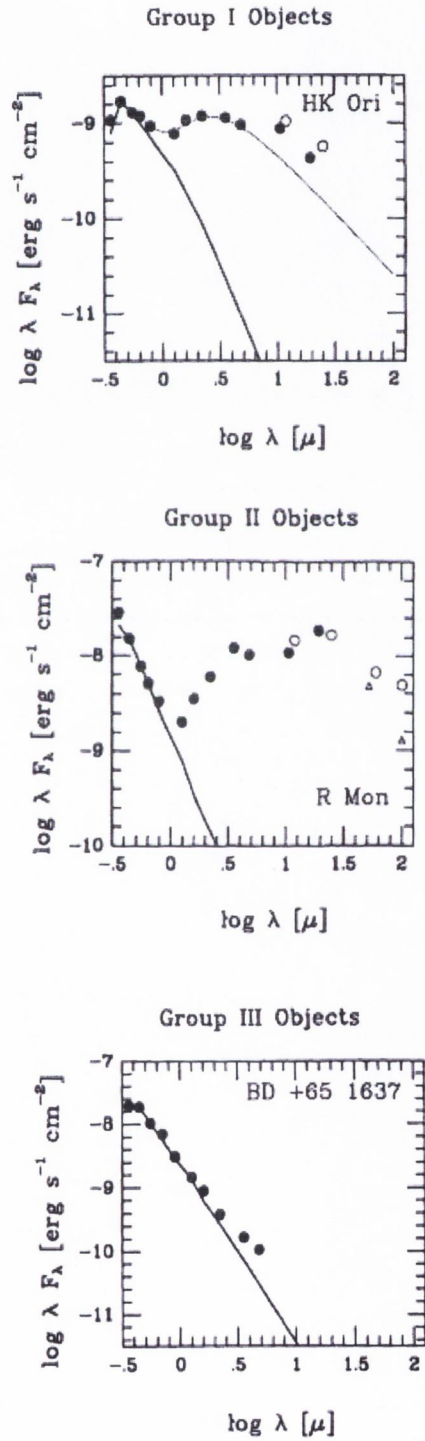


Figure 1.19: Typical SEDs of Group I, Group II and Group III Herbig Ae/Be stars taken from Hillenbrand, Strom, Vrba, & Keene (1992).

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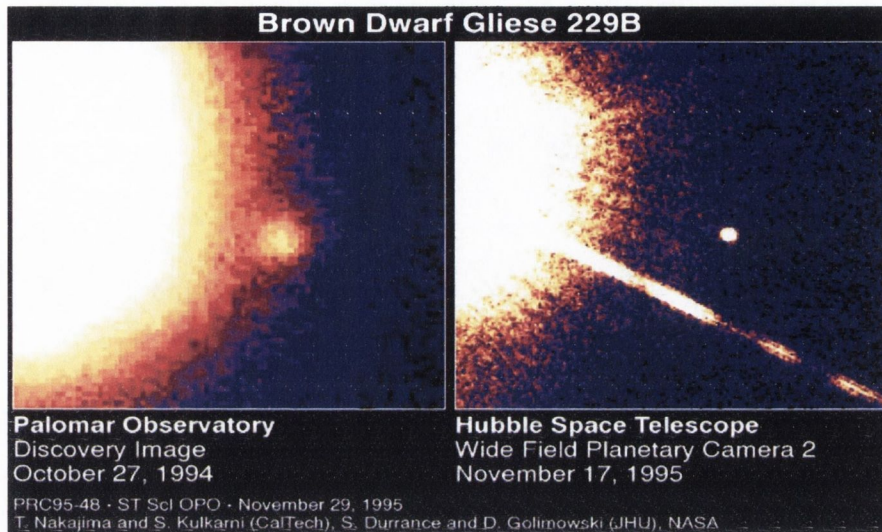


Figure 1.20: Images of the Gliese 229 system. Gl 229B the BD companion to Gl 229A was the first BD to be imaged. The discovery image was taken with the Palomar 60-inch telescope in 1994 (Nakajima et al., 1995) and was followed up with an image taken in 1997 with the WFPC2 on the HST (Golimowski et al., 1998). The mass of this BD is estimated at $0.03\text{--}0.04M_{\odot}$ and it is 2-4 billion years old.

first BDs only made these objects even more interesting and their scarcity led to the phrase “Brown Dwarf desert”. Gliese 229B, shown in Figure 1.20 was the first BD to be imaged. BDs are now known to exist in clusters (Rebolo et al., 1996) and in the field (Ruiz, Leggett, & Allard, 1997). New surveys of star forming regions (Briceño, Hartmann, Stauffer, & Martín, 1998; Wilking, Greene, & Meyer, 1999) reveal that these objects may be as common as stars and that they are produced in all possible masses between stars and planets (Basri, 2000a).

By far the most logical way to differentiate between stars, BDs and planets is through their internal physics. Nuclear reactions in the cores of normal stars inject energy thus preserving an ideal gas pressure. It is this pressure that maintains a star’s stability against gravitational collapse. For starlike objects of a low enough mass or a high enough density stability against collapse is sustained by a different source of pressure. The Pauli exclusion principle states that no two electrons can occupy the same quantum level, hence in a very dense core, where all the electrons are freed from their nuclei by the intense heat, low energy states are quickly filled and electrons are forced to occupy very high energy states. This creates a form of pressure called electron degeneracy pressure which is insensitive to temperature

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Object Type	Mass ^a ($M_{\odot}$)	H Fusion	D Fusion	Contains Li D
Very low mass Star	0.1-0.075	Sustained	Evanescent	No No
Brown Dwarf	0.075-0.065	Evanescent	Evanescent	Yes ^b No
Brown Dwarf	0.065-0.013	Never	Evanescent	Yes No
Planet	<0.013	Never	Never	Yes Yes

Table 1.1: Definitions of a Very Low Mass Star, Brown Dwarf and Planet, taken from Oppenheimer, Kulkarni, & Stauffer (2000). ^a Masses given here assume that the objects have solar metallicity. ^b Brown Dwarfs in the mass range have lithium abundances that are age dependent.

and it is this pressure that resists contraction in BDs. Fusion in normal stars halts contraction and the star achieves a steady luminosity. Normal fusion does not occur in BDs and instead energy is supplied by gravitational contraction. Because degeneracy pressure slows down the contraction of a BD, its luminosity declines so BDs fade steadily with age.

Kumar (1963) postulated the existence of BDs or Black Dwarfs, as he originally called them, when he calculated the lower mass limit of a main sequence star, i.e. the mass below which stability is maintained through electron degeneracy pressure. He gave this limiting mass as being between $0.07M_{\odot}$ and $0.09M_{\odot}$. This is now defined as the hydrogen burning mass limit (HBML), i.e. the lowest mass at which a normal star can fuse hydrogen, and modern calculations place it between $0.07M_{\odot}$ and $0.08M_{\odot}$ (Burrows & Liebert, 1993). So our definition of a BD is a starlike object that is not massive enough to fuse hydrogen, hence it is cool and gets colder with age. Even though BDs are too small for normal hydrogen fusion they do fuse deuterium for some portion of their evolution. The lower mass limit for deuterium fusion is given at $0.013M_{\odot}$. Planets, on the other hand, have no nuclear activity in their cores and the fact that they fuse nothing is what essentially separates them from BDs. Table 1.1 taken from Oppenheimer, Kulkarni, & Stauffer (2000) summarises the definitions of a star, a BD and a planet, based on their internal physics.

Now that we know that BDs exist and we are able to separate them from stars and planets we must turn our attention to how they are formed. It is possible that there is more than one mechanism for the formation of BDs and indeed this subject is much debated. The simplest idea is that they form in the same manner as low mass stars i.e. through the gravitational collapse of interstellar clouds of gas and

CHAPTER 1. Outflows from Young Stellar Objects

dust, as discussed in section 1.1. Hence it is possible that they are just scaled-down versions of TTSSs. Others suggest that the picture is not quite so simple and that BDs originate in multiple systems where fragmentation of the original core has caused three or more stellar embryos to form. The BD is the embryo that is ejected from the system hence its growth is abruptly stopped, explaining its low mass, cool temperature and its description as an unfinished star (Reipurth & Clarke, 2001; Bate, Bonnell, & Bromm, 2002). Another theory is that BDs grow in circumbinary disks in a similar way to planets (Jiang, Laughlin, & Lin, 2004).

One way in which a clearer picture regarding the formation of BDs might be obtained is to look at their accretion properties and make a comparison with low mass protostars. Many groups are involved in the study of BD accretion activity (see chapter 6 section 6.4.2) and so far they conclude that the properties of the accretion disks now known to exist around BDs are scaled down versions of T Tauri disks, pointing to a common formation mechanism for BDs and low mass stars. Given the strong relationship between accretion and outflow activity for low and intermediate mass protostars, it is natural to wonder if BDs, as a rule, also drive outflows. The only evidence that this could be possible comes from the discovery that many BDs and sub-stellar objects have strong optical FEL spectra similar to those observed for protostars. Results presented in Chapter 6 demonstrate that spectro-astrometry can be used to measure a displacement in these FELRs, proving that this emission is moving away from the BD.

So what should one expect a BD jet to be like? Masciadri & Raga (2004) model the emission of internal working surfaces produced by a radiative jet in a neutral and in a photoionised environment as a function of several jet parameters and use this model to predict the $H\alpha$ luminosity of a BD jet. Overall they conclude that a BD jet will be dynamically and morphologically similar to a CTT jet, although of course much fainter. This is based on predictions of the jet velocity and ejection velocity variability. Mass loss rate associated with BDs are predicted to be 2 orders of magnitude lower than those associated with TTSSs. As the mass loss rate is a direct indication of the mass accretion rate, lower mass loss rates for BDs mean a lower $H\alpha$ luminosity for a BD jet. The above authors find that the $H\alpha$ luminosity of a typical BD jet in a photoionised environment is 1 order of magnitude lower than for a CTT jet in a neutral environment. Masciadri & Raga (2004) suggest that the best conditions for searching for BD jets may be in regions where young low mass stars are embedded in a HII region.

Summary

Outflows are a dominant ingredient in the formation of new stars. Not only do they effect the physics of the protostars from which they are launched by dispersing the circumstellar envelope and removing angular momentum but they also strongly influence the molecular cloud with which they interact. These energetic flows were initially detected through HH objects and P-Cygni profiles and are now known to manifest themselves in many forms on both large and small scales. In this chapter the formation of large-scale HH and molecular flows was reviewed. Special attention was then paid to studies of outflows on scales as close to the central engine as possible. It is the primary wind which is launched by the central engine that excites the HH objects and drives out the molecular material surrounding the protostar in the form of a molecular outflow. Models of jet structure, launch and collimation and observations of rotation, were discussed in section 1.2.3. It is also very beneficial to the overall understanding of the outflow phenomenon to make comparisons between the outflow activity from different types of protostars. Protostars are mainly divided on the basis of mass and evolutionary stage. The final section of this chapter summarises the properties of the different categories of YSOs, i.e. embedded low mass young star, CTTSs, Herbig Ae/Be stars and finally brown dwarfs, observed for this thesis project, highlighting the characteristics of the outflows they drive.

Chapter 2

Understanding Spectro-astrometry

High resolution spectroscopic observations provide a window into the immediate environment of YSOs. In particular such studies have yielded much new information regarding outflow activity and binarity in young stars (Eisloffel et al., 2000; Takami, Bailey, & Chrysostomou, 2003). Using spectroscopy one can investigate the kinematics and excitation conditions of jets close to where they are launched and resolve close binaries. The primary constraint to the use of spectroscopy in this manner is the maximum spatial resolution achievable. Observers are all the time aiming to study outflows as close as possible to their driving sources or to minimise the smallest resolvable binary separations. This is where the technique of *spectro-astrometry* comes to the fore. Adaptive optics and interferometry are designed to overcome the limitations placed on the spatial resolution by the atmospheric seeing, however spectro-astrometry which is now described offers the observer information on comparable angular scales.

Conceptually the principles of this technique are easy to understand. Spectro-astrometry simply translates as a measurement of the position of the centroid of a flux distribution as a function of wavelength (hence velocity for a line), producing what is referred to as a “position spectrum” or spectro-astrometric plot. The profile of a star is smeared by atmospheric turbulence to appear gaussian (at least to a first approximation) rather than point-like. While the width of the profile is determined by the seeing, how accurately we can determine the centroid of the emission is, in theory (for fixed seeing), limited only by the strength of the observed signal to

CHAPTER 2. Understanding Spectro-astrometry

noise ratio (S/N). The centroid of the emission is measured by fitting a gaussian to the spatial profile extracted from the 2D spectrum, at each wavelength or pixel (see Figure 2.1). Increasing the total number of detected photons increases the astrometric accuracy so that milli-arcsecond precision is possible (Bailey, 1998a) and information may be recovered on sub-seeing scales.

A simple example to consider is the long-slit spectrum of a close binary system consisting of two virtually identical stars. If their separation is considerably less than the seeing, the profile of the system in the spatial direction will consist of a single gaussian i.e. the system is unresolved and the centroid of the emission will lie exactly between the two components. Now suppose one of the two stars differs slightly from the other in being a strong $H\alpha$ emitter. Then the emission centroid will shift towards that star in the spectrum at the position of the $H\alpha$ line. In this way it is possible to distinguish certain types of binaries below the seeing limit. In the case of a jet (pure emission line region) plus star (continuum source), one can go further and interpolate the continuum across a line thereby allowing its contribution to be removed. It is then possible to measure separately the spatial centroid of the pure ELR and determine its offset with respect to the continuum, i.e. parent star.

In this thesis spectro-astrometry is primarily used to spatially resolve multiple velocity components found in the FEL spectra of certain YSOs and to investigate the origin of other important ELRs. In section 2.1 spectro-astrometry and similar precursor techniques that have been used to date are reviewed, making particular reference to outflows. The method used to produce the position spectra presented in Chapters 3 to 6, is outlined in section 2.2. As stated above, the accuracy (in arc-seconds) of the method primarily depends on the S/N, i.e. the number of detected photons N_p . Section 2.3 is a discussion of the errors in the method.

2.1 A Brief History of Spectro-astrometry

Since the beginning of the 1980's there have been several documented approaches to the problem of extracting sub-seeing information from a flux distribution. These techniques were over time much refined to the current spectro-astrometric technique as described by Bailey (1998a). Spectro-astrometry was first applied to the study of bipolar outflows from CTTSs by Solf (1984). Altogether between 1984 and 1998 the spatial characteristics of the spectra of 12 CTTSs were investigated using spectro-

CHAPTER 2. Understanding Spectro-astrometry

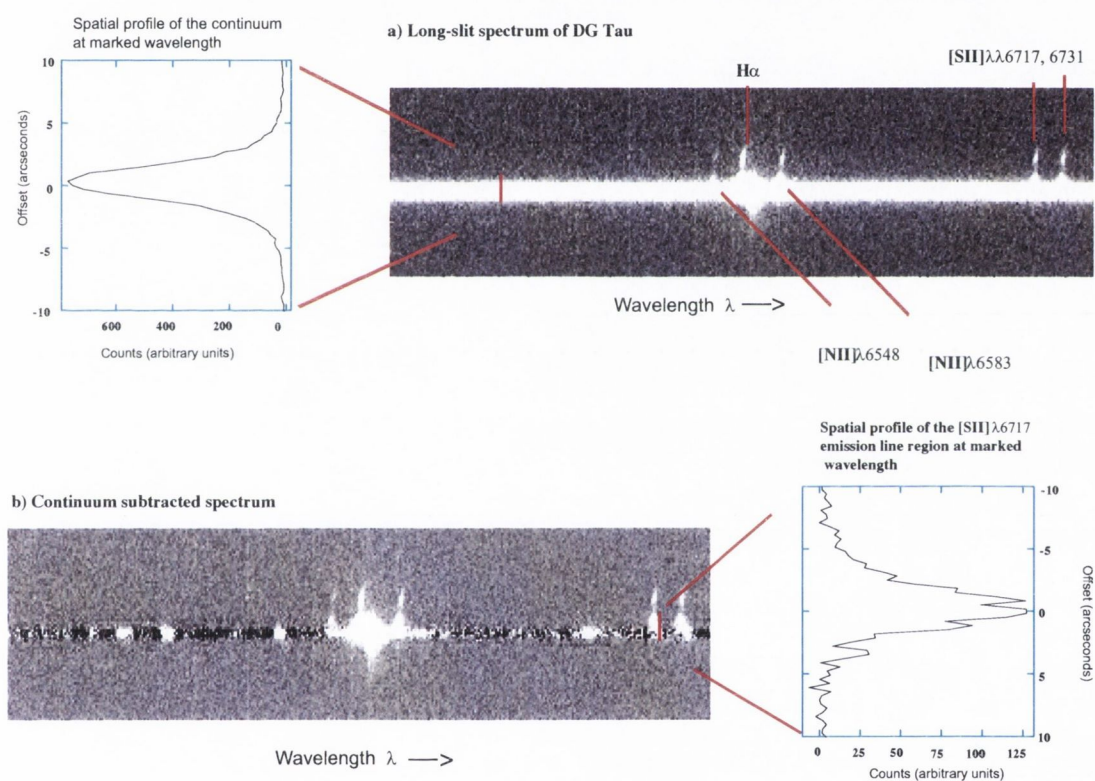


Figure 2.1: Example of applying spectro-astrometry to the long-slit spectrum of a typical CTTS, DG Tau. The extraction of a 1D spatial profile from firstly the continuum emission and then from an ELR in the continuum subtracted spectrum is illustrated. Note how easily the continuum can be removed leaving the pure ELRs exposed.

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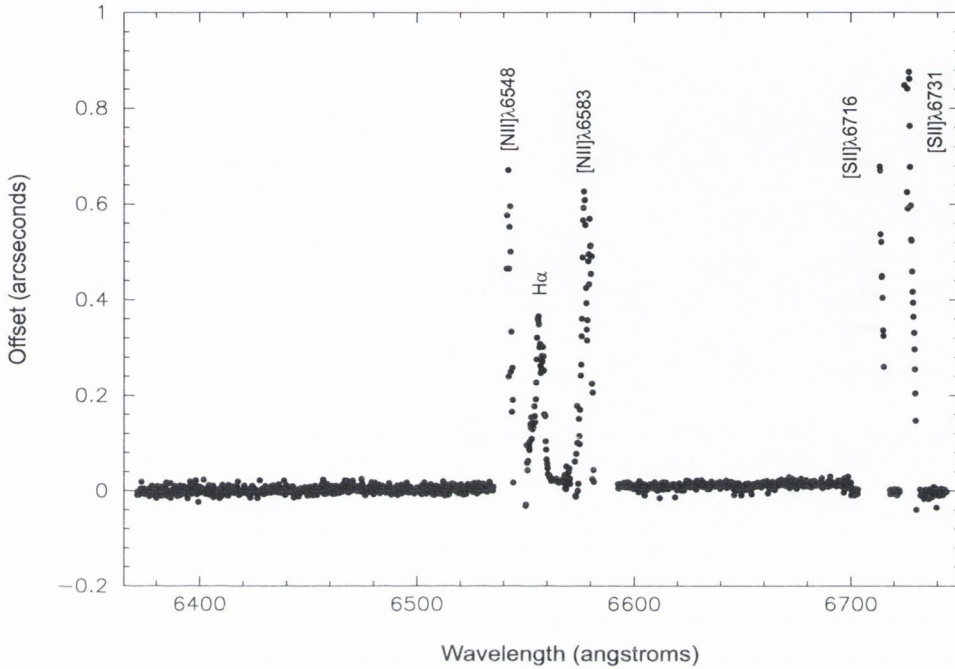


Figure 2.2: The final position spectrum obtained from the long slit spectrum of DG Tau. Note that the offsets are all to one side in the direction of the blue-shifted outflow.

astrometry (Solf, 1989; Solf & Böhm, 1993; Böhm & Solf, 1994a; Hirth, Mundt, & Solf, 1994b, 1997). The primary goal of this work was to probe the spatio-kinematic properties of the FELRs as a means of distinguishing between the different models describing their formation. By spatially resolving the FEL components the authors were able to confirm the unique origins of the different velocity components, thus verify the models of Kwan (1997) (see also Chapter 1 section 1.2.3).

Probing the spatio-kinematic properties involved measuring the relative position and spatial extent of the velocity components present. At first these values were measured by approximating each component through a 2D gaussian line distribution, which was determined using 5 parameters: (1) centroid velocity V , (2) velocity width ΔV , (3) centroid position X , (4) spatial extent $\Delta X(FWHM)$ and (5) peak Intensity I . Figure 2.3 demonstrates how Böhm & Solf (1994a) applied this method to the $[OI]\lambda 6300$ and $[SII]\lambda 6731$ FELRs of T Tau. The accuracy of this technique is limited by the assumption that the FEL components can be approximated by a gaussian distribution. Information regarding the variation of the spatial position and width as a function of velocity within a single component is also presented by

CHAPTER 2. Understanding Spectro-astrometry

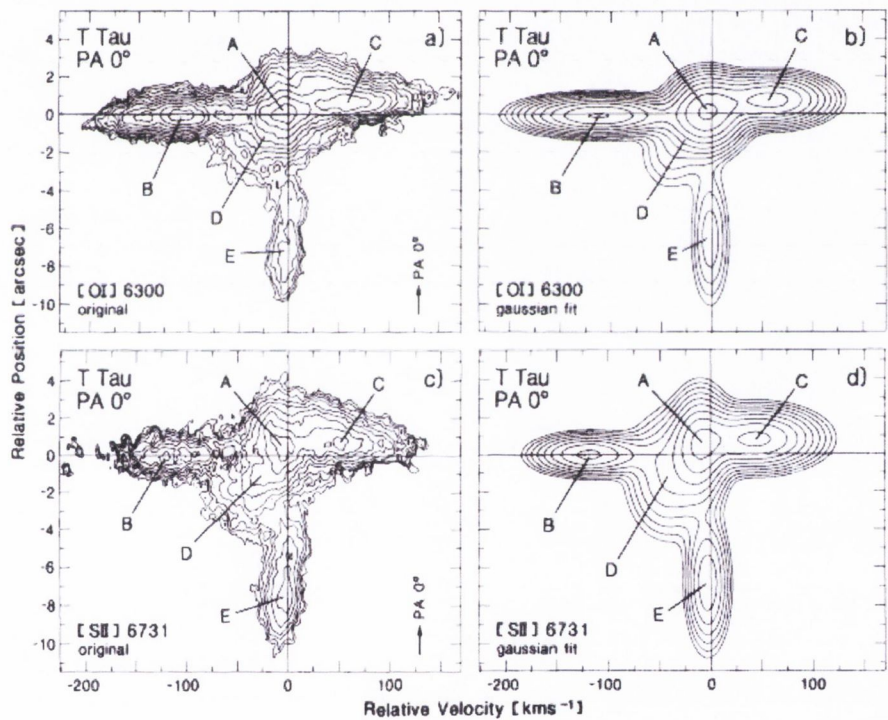


Figure 2.3: Example of how the different components present in the [OI] λ 6300 and [SII] λ 6731 FELRs of T Tau were fitted using a 2D gaussian. This diagram is taken from Böhm & Solf (1994a).

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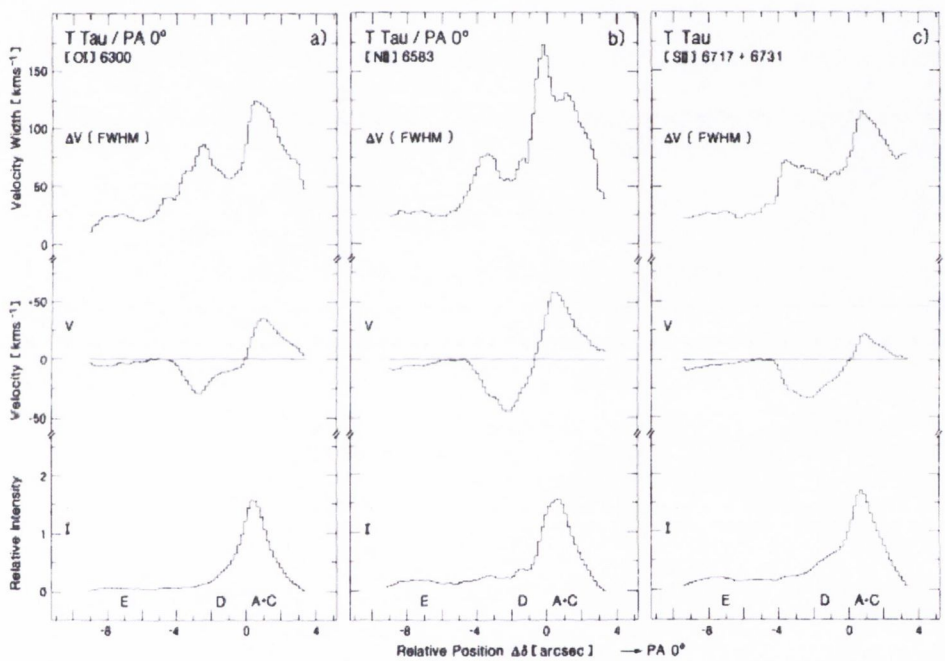


Figure 2.4: Again this diagram is taken from Böhm & Solf (1994a). It shows the spatial variations of the line intensity I , the velocity V and the velocity width ΔV as a function of position at a PA of 0°, derived for the [OI] λ 6300, [NII] λ 6583 and [SII] λ 6731 lines. The data were obtained by means of a single-component gaussian line fit and the approximate centroid positions are marked for each component except B. This figure illustrates the variation of spatial position with velocity within a single component as opposed to the variation among the individual components as shown in Figure 2.3.

CHAPTER 2. Understanding Spectro-astrometry

Böhm & Solf (1994a) (see Figure 2.4). Firstly the stellar position y_c was measured by means of a gaussian line fit in the spatial direction of the continuum in the immediate vicinity of the FELR to be studied. Secondly using the continuum-subtracted spectrum the position of the FELR y' was also measured by means of a gaussian line fit to the FEL distribution at each wavelength bin. The spatial offset of the FEL centroid at each wavelength bin is finally given as $y=y' - y_c$.

Through the work of Solf (1984, 1989) and others listed above it became possible to probe outflows from CTTSs to within ~ 100 AU of their central engines through their FELRs. Davis, Ray, Desroches, & Aspin (2001) extended this work further, in the near-infrared and used spectro-astrometry for the first time to map the position of the molecular hydrogen emission line regions (MHELRs) of a sample of Class I sources. Class I sources are still very much surrounded by gas and dust hence they are generally optically invisible and one must look to the infrared regime to observe them. In Chapter 3 I present the results of a project where the sources which were originally mapped by Davis, Ray, Desroches, & Aspin (2001) were further probed using the [FeII] line at $1.644\mu\text{m}$. Takami et al. (2001) were the first to use spectro-astrometry to probe outflow activity to milli-arcsecond levels. They measured the displacement in the $\text{H}\alpha$ line from the CTTS RU Lupi and showed that the measured offsets agreed with the spatial properties of the optical FELRs of this source. Takami, Bailey, & Chrysostomou (2003) present similar results for CS Cha and Takami et al. (2002) trace the outflow from DG Tau to within 50 mas of the driving source in the HeI line at $1.083\mu\text{m}$. The results shown in the chapters which follow greatly extend the body of work summarised here and numerous examples of where spectro-astrometry has made it possible to now study outflow activity to within 15 AU of the central engine are discussed. 15 AU equals approximately $0''.1$ at 150 pc (the nearest star forming regions).

It is also important to briefly mention the projects that have used techniques similar to spectro-astrometry, and spectro-astrometry itself to study binarity in YSOs. The question of resolving spectroscopic binaries that are closer than the seeing was originally tackled using methods such as Differential Speckle Interferometry (DSI) or Chromatic Position Difference (CPD). DSI basically measures the difference in the position of the speckles in two simultaneous images at different wavelengths. Binary stars, which have a large colour difference, will be detected by a shift in the photocentres of the speckles as a function of wavelength. The magnitude of the photocentre displacement is related to the binary separation and

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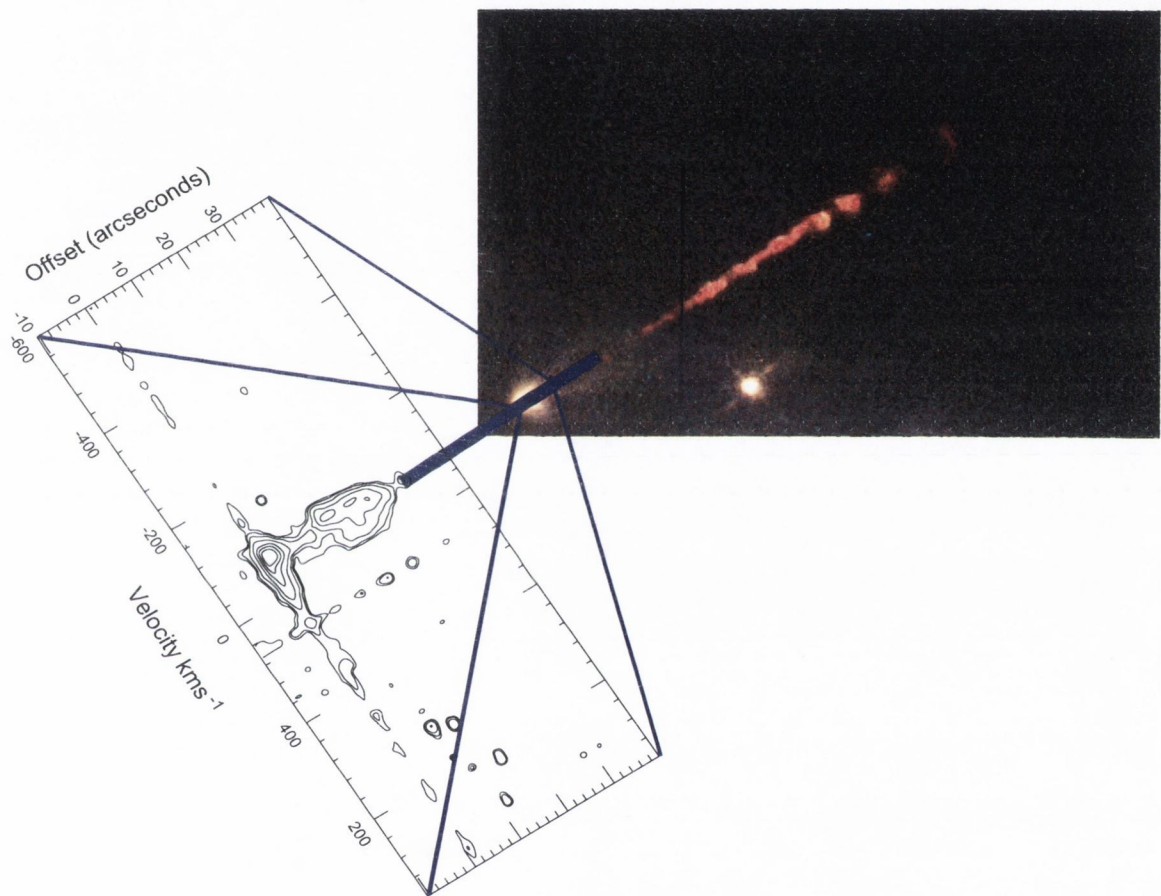


Figure 2.5: HST Wide-Field Planetary Camera II image of the collimated outflow from the Class I YSO HH 34 and the corresponding United Kingdom Infrared Telescope (UKIRT) [FeII] 1.644 μ m spectrum (see also Chapter 3). The observation was obtained by aligning the instrument slit with the previously known axis of the outflow. In the spectrum one can clearly make out strong emission from the source, a weak continuum and emission from the closest knot.

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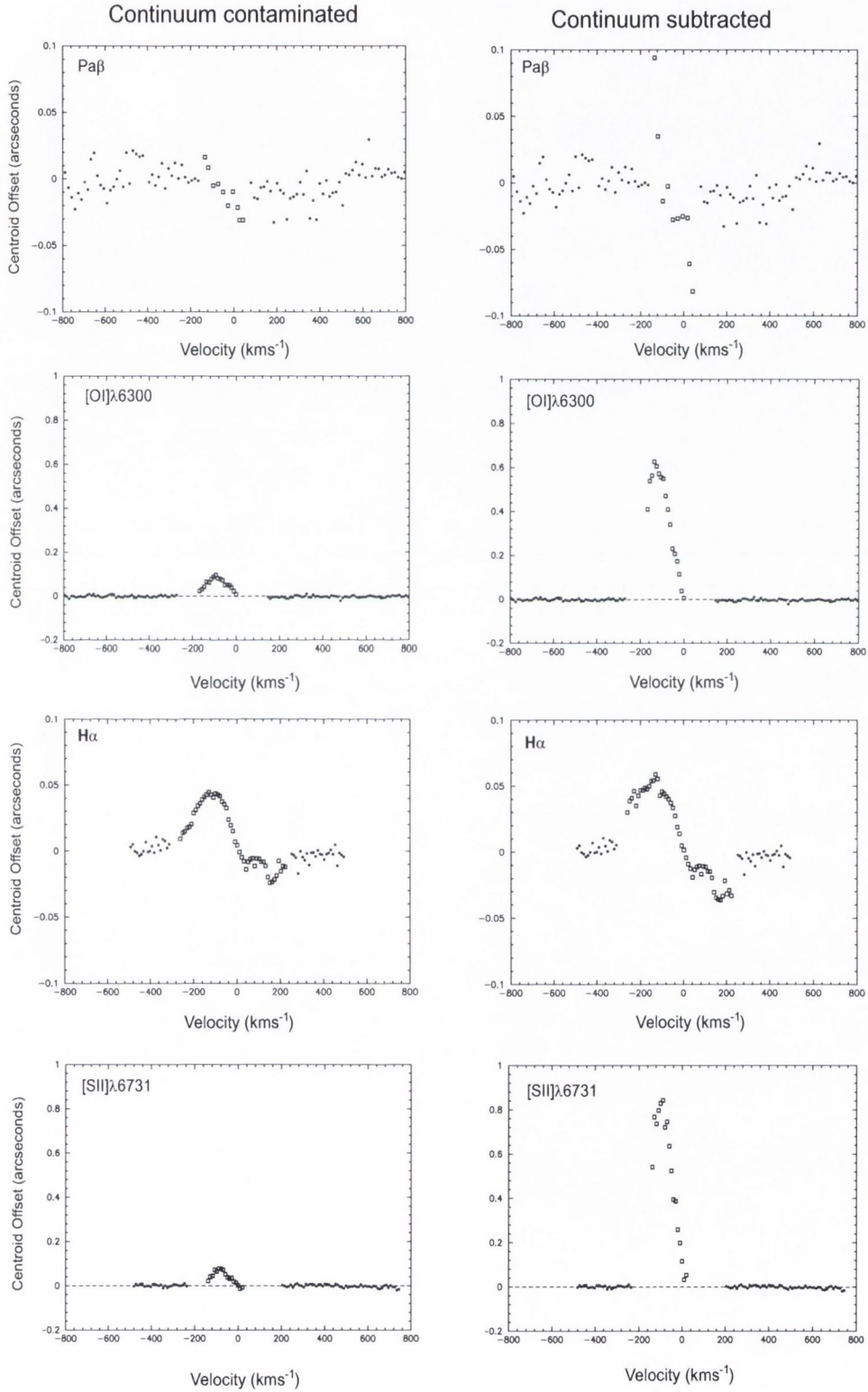


Figure 2.6: Position spectra of forbidden and permitted lines of V536 Aql extracted from the raw (i.e. continuum contaminated, left panel) and continuum subtracted spectra (right panel).

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the direction of the displacement gives an indication of the position angle of the binary (Petrov & Lagarde, 1992; Petrov, Lagarde, & N'guyen van Ky, 1996). CPD is a very similar technique to DSI and also works on the premise that if binary components differ in colour the photocentre coordinates will depend on wavelength (Sorokin, 1985).

Bailey (1998a) coined the term spectro-astrometry when he described how a technique very similar to that used by, for example Hirth, Mundt, & Solf (1997) to study outflows, could be used to separate spectroscopic binaries. If a simple long-slit spectrum is actually composed of two stars of small separation, the position spectrum extracted from the long-slit data will alter notably with wavelength as the relative contributions of the two stars to the spectrum change. As this method is far simpler than either DSI or CPD in that it does not require elaborate instrumental set-ups or involve complex data reduction techniques, it is beginning to be used more extensively. For a thorough insight into the work done to date using spectro-astrometry to study binarity in YSOs see (Bailey, 1998b; Takami, Bailey, & Chrysostomou, 2003; Baines et al., 2004).

2.2 The Spectro-astrometric technique

In chapters 3 to 6 I present and discuss numerous spectro-astrometric plots of the ELRs found in the spectra of a variety of YSOs. Altogether I study the spatial properties of the spectra of three Class I low mass sources, four CTTs, four Herbig Ae/Be stars and one BD. In this section I shall outline the general steps I took to prepare the position spectra of these sources. Figure 2.1 summarises the overall process.

1. *Obviously the first stage of the process is to obtain suitable spectroscopic data.*

Ideally one needs an intermediate dispersion, high S/N long-slit or echelle spectrum. The intermediate dispersion ensures that the ELRs are well resolved spectrally without sacrificing S/N. A high S/N is necessary for astrometric accuracy (see section 2.3). In particular, note that using a higher spectral resolution may only give rise to additional noise (e.g. from the detector) without any further gain in information.

When deciding on the type of detector one should primarily look at the pixel scale. Considering only pure stellar emission, any displacement (in arcsec-

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onds) of the spatial profile normally translates to only a small fraction of a pixel. Therefore in order to have a very accurate measurement of the centre of the continuum i.e. the position of the star, it is a requirement that the seeing profile be Nyquist sampled by the pixel scale. In other words the full width half maximum of the spatial profile should be spread across two or more pixels. Hence if using a detector with relatively large pixels, good seeing which is important for good spectro-astrometric accuracy can become a problem. Appendix B is a further discussion of the trade off between pixel size and seeing. It also includes Table B.1, listing the seeing and the pixel scale of every observation which was analysed using spectro-astrometry.

2. *The next important consideration is the position angle (P.A.) at which the spectrum is to be taken.* All sources discussed in this thesis, except of course the BDs, were previously known to be drivers of outflows and in each case the P.A. of the outflow had been recorded or at least estimated. Hence it was possible to align the slit with the outflow axis. In Figure 2.5 this set-up is illustrated this. Aligning the slit along the direction of the outflow ensures that any spectro-astrometric offset is normally maximised.
3. *The initial data reduction i.e. flat-fielding and wavelength calibration, was done using standard IRAF routines.* The initial data reduction is discussed for each different study in Chapters 3 to 6. It is important that the flat-fielding is done in the best possible fashion using very high S/N flat fields. Any non-uniformity in the pixel to pixel response of the spectrum could theoretically introduce structure into the position spectrum which might be confused with a real spectro-astrometric detection. In the majority of cases the spectrum, due to misalignment effects of the optics, is curved and/or tilted. It is necessary that these effects be removed. A function describing the position of the centre of the spectrum across the whole wavelength range is created using the *identify*, *reidentify* and *fitcoords* IRAF routines and a fit to this function is applied to the spectrum to straighten it¹
4. *A simple IRAF script is used to measure the position of the continuum emission at each pixel.* This whole process is summarised in Figure 2.1. The IRAF

¹It was not found that straightening the spectrum in this manner introduced any errors into the measurement of the spectro-astrometric accuracy

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splot task allows the user to display and interactively analyse spectra. In particular one can easily use this interactive task to extract a spatial profile from a 2D spectrum and then fit a gaussian to the profile. Figure 2.8(a) illustrates how *splot* extracts a pure continuum spatial profile before fitting a gaussian to it. The fitting routine employed by *splot* outputs the position centroid and the full width half maximum (FWHM) of the profile and estimates the flux in counts. The accuracy of the technique is increased by binning the spectrum so that, for example, each spatial profile is the average of several adjacent profiles. Once the position of the continuum is measured for the whole spectrum one can check how successful the method for removing any curvature and/or tilt in the spectrum outlined above (in step 3), was by fitting the continuum points. The spectro-astrometric plot of the continuum emission should be fitted by a straight line through zero. Any residual misalignment effects of the optics are simply removed by subtracting the fit to the continuum points (refer to Figure 2.9).

5. *The next step is the continuum subtraction.* If one is considering for example only the ELRs, the raw spectrum i.e. before the continuum subtraction, is in effect “contaminated” by the continuum. The effect this contamination has on the position spectra is that one measures a position for the ELR + continuum which, of course is closer to the star than that of the pure ELR. Essentially the displacements measured are dragged towards the continuum emission. It is important in the context of this thesis work at least that the true offsets of the different ELRs are recorded. There are two approaches one can take to this problem. Firstly it is possible to simply subtract the continuum emission from the spectrum and then measure the position of the ELRs using the continuum subtracted spectrum. An alternative approach adopted by Takami et al. (2001) and Takami, Bailey, & Chrysostomou (2003) is to correct for the effect of the continuum by calculating the factor by which the offsets are weighted by the continuum and dividing the raw positional displacement by this number. Takami et al. (2001) give this factor as

$$I_{\lambda(line)} / [I_{\lambda(line)} + I_{\lambda(cont)}] \quad (2.1)$$

Both approaches should yield similar results and in this thesis the continuum

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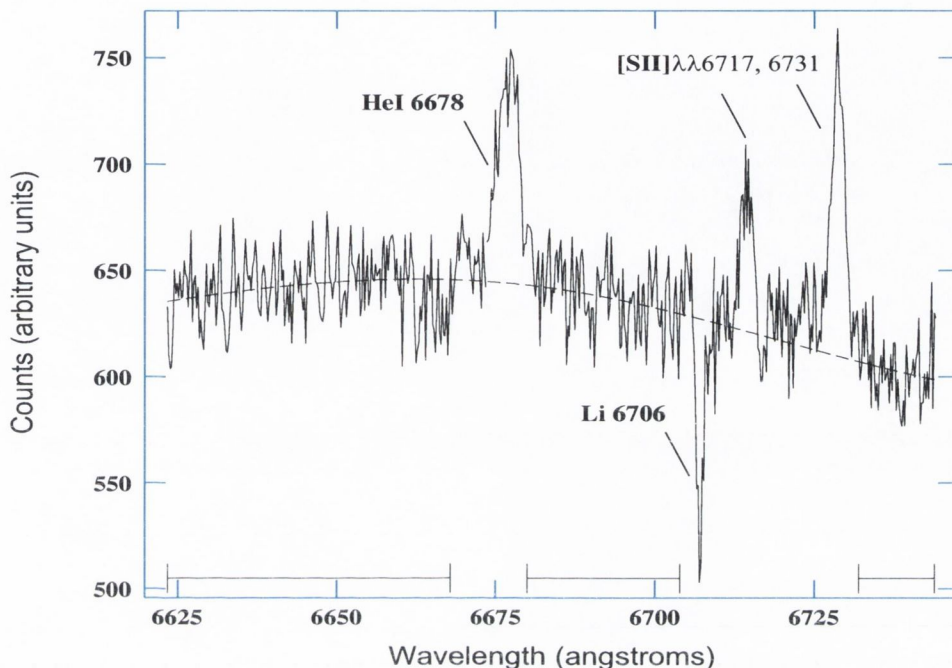


Figure 2.7: Example illustrating the continuum subtraction procedure, using a section of the optical spectrum of DG Tau. The continuum at each dispersion line (over which the continuum emission is spread) is fitted such that strong ELRs such as [SII] $\lambda\lambda$ 6716,6731 shown above are not included in the fit. The barred lines show the part of the spectrum included in the fit of the continuum.

subtraction method is arbitrarily preferred. As an example in Figure 2.6 the spectro-astrometric plots of some of the optical/NIR emission lines found in the spectra of the CTTS V536 Aql are shown. In all cases I measure the offsets in the raw and continuum subtracted spectrum and compare the measured displacements. For the FELs offsets are typically on the order of hundreds of milli-arcseconds hence it is still obvious even from the raw position spectrum that the FELRs are displaced in the direction of the V536 Aql blue-shifted outflow. The ELR + continuum offsets are however typically only a fraction of their true value as is clear from Figure 2.6. For the H α line the displacement is little effected by the continuum contamination as the intensity of the H α line is much stronger than the continuum intensity.

The continuum subtraction is easily done using the IRAF *continuum task*. For a strong continuum, emission is spread over a substantial number of dispersion lines. Once the range of lines over which the continuum emission is spread

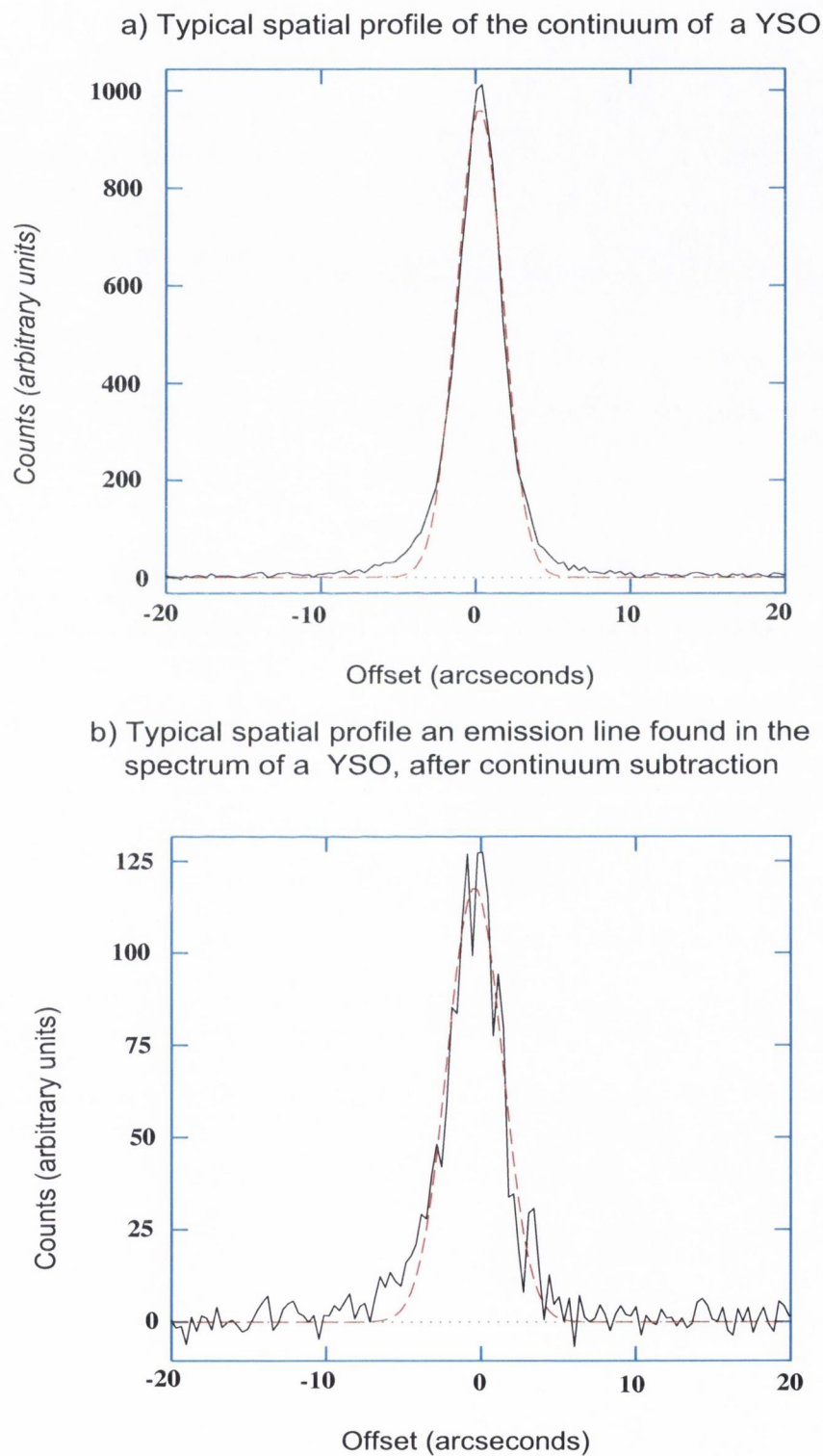


Figure 2.8: Illustration of how *splot* is used to extract and gaussian fit spatial profiles of the continuum and line emission.

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Instrument	Detector	Gain(electrons/ADU)
CGS4	fpa046	6
IDS	EEV10	2.11
	Tek3	0.7
UVES	ccdUvR	1.53

Table 2.1: Three different instruments were used to obtain the observations discussed in this project. The various detectors used with these instruments and their gain in electrons/ADU are listed above.

is specified, the *continuum* task selects the first line in the range, fits a 2D polynomial to the this line (ignoring the ELRs) and then subtracts this fit. In this way the continuum is removed line by line. One ensures that the ELRs are not included in the fit to the continuum by using the *sample* parameter to specify the parts of the spectrum that are pure continuum emission and ignore the parts that are line emission. One can also check the fit and alter the order of the fit and the type of function at each line. Figure 2.7 illustrates the fit to the continuum for one line of a typical optical long-slit spectrum of a YSO. Also in Figure 2.1 I show the raw and continuum subtracted optical spectrum of DG Tau.

6. *Once the continuum is subtracted any displacement in the pure ELR relative to the centre of the continuum can finally be measured.* Again the *splot* task is used, in exactly the same way as described in step 4, to extract a spatial profile from a pure ELR and fit a gaussian to the profile. Figure 2.1 illustrates this process and the spectro-astrometric plot of the ELRs in the optical spectrum of DG Tau is shown in Figure 2.2. As mentioned in step 4 any residual tilt or curvature in the spectrum is removed from the plot of the continuum position by fitting the continuum points and subtracting the fit. Obviously it is necessary that this fit also be removed from the position spectrum of the ELRs.

2.3 Spectro-astrometric accuracy

While the angular width of the flux distribution for a point source, is set by the seeing, the centroid of the gaussian fit is measured to an accuracy given by

$$\sigma_{centroid} = \frac{seeing(mas)}{2.3548\sqrt{N_p}} \quad (2.2)$$

where N_p is the number of detected photons. Here the seeing is the FWHM of the distribution. We had assumed the only source of noise is photon noise and that the distribution is better than Nyquist sampled. As any variation in the seeing with wavelength is assumed to be small, a fixed average seeing is used when calculating the errors. Note also that the total wavelength range being considered is short.

Assuming a fixed average seeing means that the precision in the measurements is dominated by N_p . As described in section 2.2 the *splot* task used to extract and fit the spatial profile at each wavelength (pixel) also estimates the flux in number of counts (N_c) for each extracted profile. N_c is of course related to N_p when allowance is made for the system gain. If considering the continuum emission only, $\sigma_{centroid}$ is alternatively measured as the standard deviation in the position of the continuum, $\sigma_{scatter}$ say. As the position of the continuum emission is measured at each wavelength a spectro-astrometric plot of a pure continuum source appears as a scatter about zero.

Observations presented in this thesis were taken with three different instruments on three different telescopes. The Cooled Grating Spectrometer No. 4 (CGS4) on UKIRT, the Intermediate Dispersion Spectrometer (IDS) on the Isaac Newton Telescope (INT) and the UV-Visual Echelle Spectrograph (UVES) on the Very Large Telescope (VLT). In Table 2.1 the detectors used with the above instruments and the gain of these detectors in electrons per ADU are listed. Two different detectors were used for the observations taken with the IDS. In Table 2.2 $\sigma_{centroid}$ is compared to $\sigma_{scatter}$ for a small sample of sources. In each case the continuum region being considered and the instrument used in the observation is also listed. To measure $\sigma_{centroid}$, N_c , corrected for the gain of the detector is substituted for N_p in equation 2.8. Theoretically $\sigma_{centroid}$ should equal $\sigma_{scatter}$ and overall they are similar. In reality I found it easier to define the accuracy of the spectro-astrometric technique using $\sigma_{scatter}$.

Above and in Table 2.2 the accuracy in the measured position of the continuum

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Source	Continuum Region	Instrument	$\sigma_{centroid}$ (mas)	$\sigma_{scatter}$ (mas)
DG Tau	Pa β	CGS4	13	14
V536 Aql	[SII] λ 6731	IDS(EEV10)	10	7
LkH α 321	H α	IDS(EEV10)	7	4
ρ -OPh 102	[OI] λ 6300	UVES	17	16
	H α	UVES	5	6
	[SII] λ 6731	UVES	18	16
R Mon	H α	IDS(Tek3)	9	11

Table 2.2: The position of the centroid of the continuum (source position) is estimated from a gaussian fit to an extracted spatial profile. Formally the error in this position is estimated from equation 2.8. Alternatively this error also corresponds to the standard deviation in the scatter of the continuum points about zero $\sigma_{scatter}$. $\sigma_{centroid}$ and $\sigma_{scatter}$ are compared above for a sample of sources.

only is considered. While the accuracy is constant across the continuum, moving from the continuum into the line region causes a change in the error primarily due to an increase or decrease in the value of N_p . Moreover one must also consider how the line and continuum are related spatially. If, and only if the line and continuum are totally separate does the error in the position of the line depend on $N_p(L)$ (the number of detected photons at the line). If the line and continuum are spatially coincident then one must also consider the number of detected continuum photons $N_p(c)$. This is a complicated question and accurate modelling is required to satisfactorily answer it.

Summary

Spectro-astrometry allows the observer to extract sub-seeing spatio-kinematic information from a spectrum. The simplicity and effectiveness of this technique has meant that it has enormous potential in the study of YSOs. Spectro-astrometric observations are straightforward as they simply require a high S/N, high spectral resolution spectrum, something which is easily acquired. They are also very effective as the main limitation to their performance is the S/N of the observation and in particular the seeing and the number of detected photons N_p . In this chapter I have outlined the ways in which a small group of observers have taken advantage of the power of spectro-astrometry in probing outflow activity from YSOs. I

CHAPTER 2. Understanding Spectro-astrometry

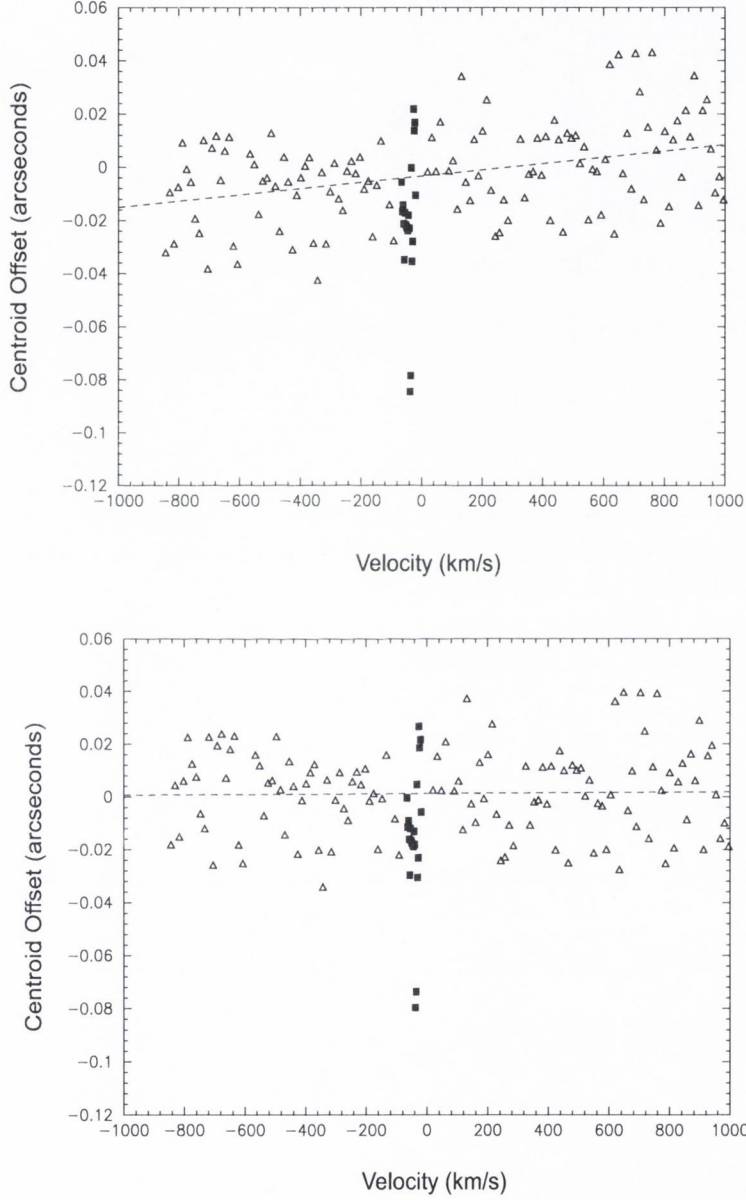


Figure 2.9: Position spectra of the $[\text{OI}]\lambda 6300$ emission from the BD ρ -Oph 102 (see Chapter 6), before (top) and after (bottom) continuum straightening. A second order polynomial fit is made to the continuum and this fit is subtracted from the continuum and emission line points to correct for any residual tilting or curvature from the optics.

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have discussed the procedure I use to produce spectro-astrometric plots from simple spectra, including a discussion of spectro-astrometric accuracy. In Chapter 7 some of the ways in which it may be possible to attain better observations than those presently possible by combining spectro-astrometry with interferometric and adaptive optics techniques or by adding a second dimension to the observations using an IFU are considered. In the following chapters the results of four separate studies, all of which attest to the power and usefulness of spectro-astrometry are discussed. This work clearly demonstrates how, by taking advantage of spectro-astrometry, I have gained new and interesting insights into the central engines of YSOs from which outflows are launched.

Chapter 3

Investigating the Forbidden Emission Line Regions of Class I Protostars

Introduction

As stated the aim of this thesis project is to further explore the region close to a central protostar from which outflows are launched. Most of the information gathered to date concerning the jet launch region comes from the optically visible CTTSs (Class II YSOs), yet the embedded Class I objects, the precursors to the CTTSs, drive the majority of known outflows and represent a much earlier stage in the evolution of a star. Hence studying the central region of a sample of Class I sources will provide a further understanding of the evolution of the outflow phenomenon. CTTSs are optically visible making it easier to explore the environment immediate to their central engines, however it is now just as possible to study Class I sources in the near-infrared.

The insight that long slit spectroscopic and spectro-astrometric observations of the optical FELRs of the CTTSs have given into outflow activity close to CTTSs is reviewed in Chapters 1 and 2. To summarise observations of the FELRs of CTTSs revealed the presence of two velocity components which are described by Kwan (1997) to be representative of two outflow components consisting of a well-collimated fast jet and a wide, slower, disk wind. Studies of the spatial properties of the optical FELRs have confirmed the separate origins of the different velocity components

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Source	RA (J2000)	Dec (J2000)	Slit PA
SVS 13	03 29 03.7	+31 16 02	123°
IRAS 04239+2436	04 26 56.4	+24 43 36	59°
L1551-IRS5	04 31 33.6	+18 08 11	66°
HH 34-IRS	05 35 29.8	-06 26 58	167°
HH 379-IRS	21 45 08.2	+47 33 07	82°

¹ Slit position angle (east of north)

Table 3.1: Right Ascension, Declination and Position Angle (P.A.) of all Class I sources included in this study.

(Hirth, Mundt, & Solf, 1997). Davis, Ray, Desroches, & Aspin (2001) studied the molecular hydrogen emission lines (MHELs) of a sample of Class I protostars. The MHELs were very similar to the FELRs of the CTTSs in that they were generally blue-shifted and often multi-component. The above authors also used spectroastrometry to study the spatial properties of the MHELs revealing again a strong similarity to optical FELRs. The H₂ was generally offset from the continuum with high velocity emission offset further than the low velocity emission. MHEL regions are of considerable interest as the survival of H₂ in the inner jet regions constrains models of jet acceleration, collimation and evolution within ~ 100 AU of the outflow source.

The goal of the work presented here is to study the [FeII] 1.644 μ m ELRs of some of the Class I protostars originally observed in H₂ by Davis, Ray, Desroches, & Aspin (2001) and compare the near-infrared FELRs to the optical FELRs of the CTTSs and to the MHELs. Firstly results will reveal if [FeII] is as effective a probe of outflow activity as say [SII] $\lambda\lambda 6716, 6731$ is for the CTTSs. Previous studies have shown that the 1.644 μ m line traces regions of moderate-excitation outflows from CTTSs (Hamann, 1994). Secondly H₂ and [FeII] trace totally different conditions. In contrast to [FeII] the shock excited H₂ originates from dense (10^4 cm⁻³), warm (~ 2000 K) molecular gas of relatively low excitation, while transitions of species like [FeII] dominate cooling at similar densities though higher temperatures of the order of 10^4 K. A comparison between the MHEL and [FeII] FELR of a given source will provide information on the different outflow components contributing to the FEL and MHEL profiles.

3.1 Observations

Near-infrared echelle spectra centred on the [FeII] emission line ($\lambda_{vac} = 1.643998\mu\text{m}$), were obtained for the 6 Class I sources listed in Table 3.1. Observations were taken at UKIRT on 1-3 November 2001 UT using CGS4. CGS4 is a $1\text{-}5\mu\text{m}$ multi-purpose grating spectrometer containing a 256×256 InSb array. The pixel scale at $1.644\mu\text{m}$ for a grating angle of 62.75° measured $0''.88 \times 0''.41$ in the spatial and spectral directions respectively. The seeing was measured for each of the observations analysed with spectro-astrometry and is given in table B.1 (see Appendix B). A slit width of two pixels gave a velocity resolution of $\sim 8 \text{ kms}^{-1}$.

In each observation the slit was orientated along the jet axis with the source in the centre. Position angles for each of the sources are shown in Table 3.1. Positioning the slit along the jet axis ensured that measured displacements in the emission line region were maximised. In all cases a sequence comprising one sky exposure followed by three object exposures in order to build up signal to noise. The sky position was typically $30''$ to $60''$ away from each source in a direction orthogonal to the flow axis. Each sky-subtracted spectral image was then bias subtracted, flatfielded and co-added into reduced groups.

The data reduction was done using standard IRAF routines. A krypton-argon arc spectrum was taken immediately prior to each object exposure and used to wavelength calibrate the data. However only six lines spread across the dispersion axis could be used for accurate wavelength calibration. The argon and krypton lines at $\lambda_{vac}=1.644107 \mu\text{m}$ and $1.647035 \mu\text{m}$ were observed directly (in the 33rd order) while lines at $1.694521 \mu\text{m}$ and $1.599386 \mu\text{m}$ (argon) and $1.670137 \mu\text{m}$ and $1.694043 \mu\text{m}$ (krypton) were detected from adjacent (32nd or 34th) orders. The [FeII] line lies close to the bright OH sky line, OH(5,3)R₁(2) at $1.64421 \mu\text{m}$ (Maihara et al., 1993) which could therefore be used to check the velocity calibration. The arc spectral images were self-calibrated in order to also check for variations in the absolute wavelength calibration. These variations were found to be small, of the order of 5 kms^{-1} towards the edges of the array, and a factor of two better within the central 30%, where the [FeII] emission was observed. Instrument flexure over the duration of the observations can introduce uncertainties in the absolute velocity calibration, i.e. by shifting the individual frames with respect to the wavelength reference used to calibrate the reduced group spectral image. By comparing the positions of the sky lines in a number of raw frames it was found that this effect was small. The

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overall velocity calibration was found to be accurate to better than $\pm 6 \text{ kms}^{-1}$.

3.2 Results

My aim is to discuss the potential of [FeII] as a tracer of outflows from Class I sources from which H_2 emission has already been observed and to make a comparison with observations of optical FELs from Class II sources and with the H_2 observations. Consequently I present continuum subtracted position velocity diagrams for each of the sources considered in this study. For three of the sources SVS13, IRAS04239+2436 and L1551-IRS5 emission line profiles and corresponding spectro-astrometric plots are shown in Figure 3.7. Both HH 34 and HH 379 had only a very weak continuum in the vicinity of the [FeII] line, hence it was not possible to accurately measure the source position. The spectro-astrometric method and the estimation of errors are described in Chapter 2. The [FeII] continuum and line emission is in general weak compared to the optical and near-infrared spectra discussed in Chapters 4 and 5 hence the errors recorded here are relatively large. The average error for the continuum position is estimated at $\sim 42 \text{ mas}$ and for the line emission is $\sim 46 \text{ mas}$.

3.2.1 SVS 13 (HH7-11)

SVS 13 in NGC1333 ($d \sim 220 \text{ pc}$) was discovered at $2.2 \mu\text{m}$ by Strom, Vrba, & Strom (1976) and it has been observed extensively since then at NIR wavelengths (Garden, Russell, & Burton, 1990; Stapelfeldt et al., 1991; Carr, 1993; Gredel, 1996; Chrysostomou et al., 2000; Khanzadyan et al., 2003). It is known to have undergone an outburst in recent years (Eisloffel et al., 1991) and from Davis, Stern, Ray, & Chrysostomou (2002) it is clearly associated with complex H_2 emission. SVS13 also has an optical counterpart (Goodrich, 1986a) yet it presents characteristics that suggest it is in a Class I object in a late stage. For example it is a strong millimeter source (Looney, Mundy, & Welch, 2000) and it drives a high velocity CO outflow (Bachiller et al., 2000).

As it is roughly aligned with the chain of HH objects HH7-11 (Herbig, 1974; Strom, Grasdalen, & Strom, 1974) it is assumed to be the exciting source of this HH system. The HH objects themselves reside along the edges of a south-eastern, blue-shifted cavity that is bounded by a fast-moving molecular shell (Bachiller &

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Cernicharo, 1990; Bachiller et al., 2000). A high angular resolution radio map of this region detected SVS 13 as the radio centimeter source VLA 4 and a new object, VLA 3 some $6''$ to the south-west (Rodríguez, Anglada, & Curiel, 1997).

Recent VLA observations by Anglada et al. (2004); Anglada, Rodríguez, & Torrelles (2000), confirmed these findings and resolved VLA 4 into a close binary VLA 4A and VLA 4B. The two components are separated by $0''.3$ or 65 AU at 200 pc and a lower limit of 135 yr is derived for the orbital period of the binary system. Based on their radio data Anglada, Rodríguez, & Torrelles (2000) suggest an interesting interpretation of all the data on this source. They claim the VLA 4A is associated with the optical counterpart of SVS 13 and VLA 4B with the millimeter counterpart. If VLA 4B were surrounded by a dusty disk any change in the accretion of this disk could lead to sudden brightening of SVS 13 in the optical as observed by Eisloffel et al. (1991). Anglada et al. (2004) confirm the presence of a single disk in the SVS 13 close binary system around VLA 4B.

Davis, Ray, Desroches, & Aspin (2001) detected strong H_2 emission towards SVS 13 and out along the HH7-11 flow axis. The H_2 spectrum of this flow was made available to me through private communication (C.J. Davis) and the position velocity diagram of the HH 7-11 region in H_2 is shown in Figure 3.1. The H_2 emission at the source is seen to be double peaked with a HVC at $\sim -90 \text{ km s}^{-1}$ and a LVC at $\sim -20 \text{ km s}^{-1}$ and spectro-astrometry shows that the high velocity emission is offset to $\sim 0''.4$ and the low velocity emission to $\sim 0''.2$. A LVC and HVC are also observed in [FeII] (see Figure 3.2). The HVC is strong and peaks in intensity at a velocity $\sim -133 (\pm 10)$. The LVC is much weaker and peaks somewhere in the range -20 to -50 km s^{-1} . The results of applying the spectro-astrometric technique to this spectrum are shown in Figure 3.7. The high velocity emission is displaced to approximately 80 mas.

3.2.2 IRAS 04239+2436 (HH 300)

This low luminosity ($L_\star \sim 1.3L_\odot$) embedded protostar lies in the B 18 cloud in Taurus at a distance of ~ 140 pc and it is known to have a rich near-infrared spectrum (Greene & Lada, 1996). It is the exciting source of a well-collimated, knotty jet of about $10''$ in length. This jet was observed in detail by Reipurth et al. (2000) using NICMOS on the HST however the jet within $1''$ of the source was obscured by the intense stellar continuum. The HH 300 knots labelled A to

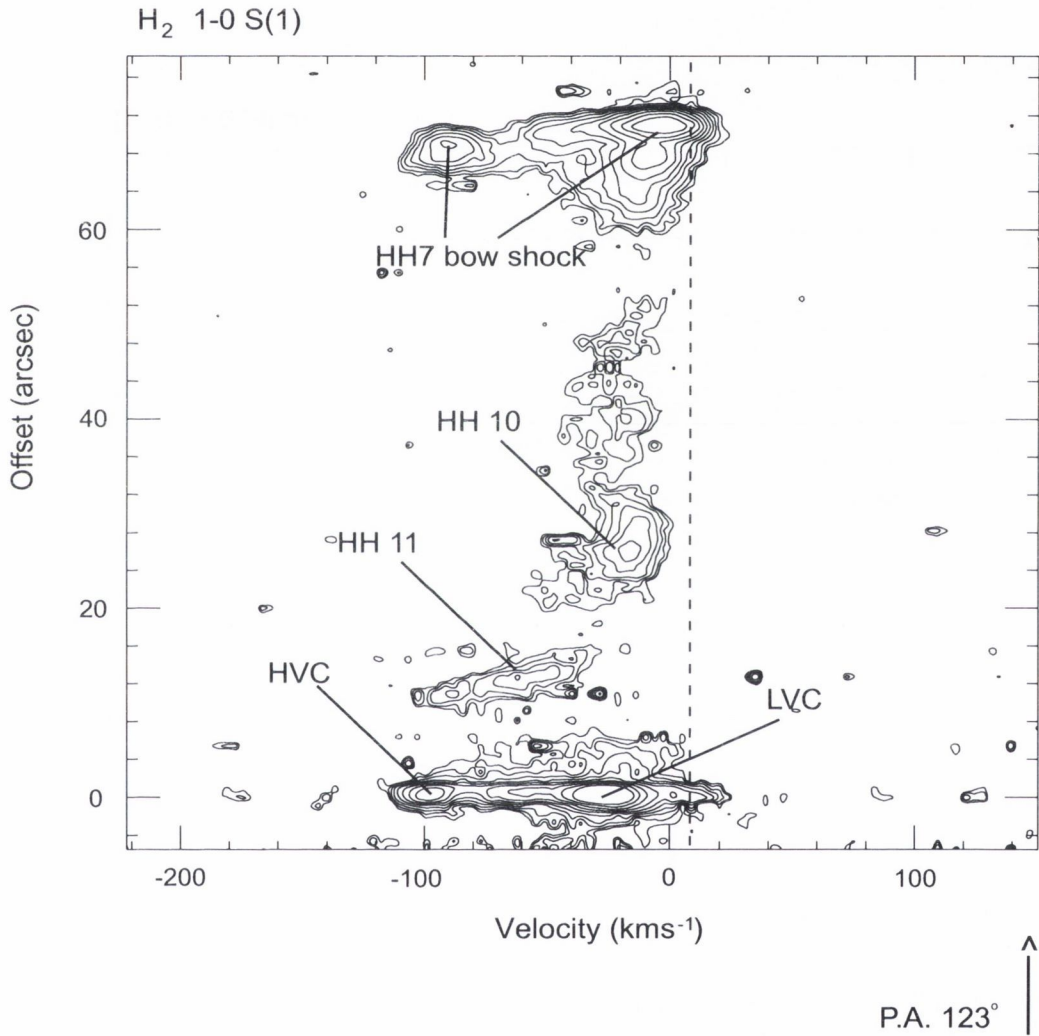


Figure 3.1: Continuum-subtracted position velocity diagram of the H₂ emission from SVS 13 and associated HH objects. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. The dashed line marks the systemic velocity of the source.

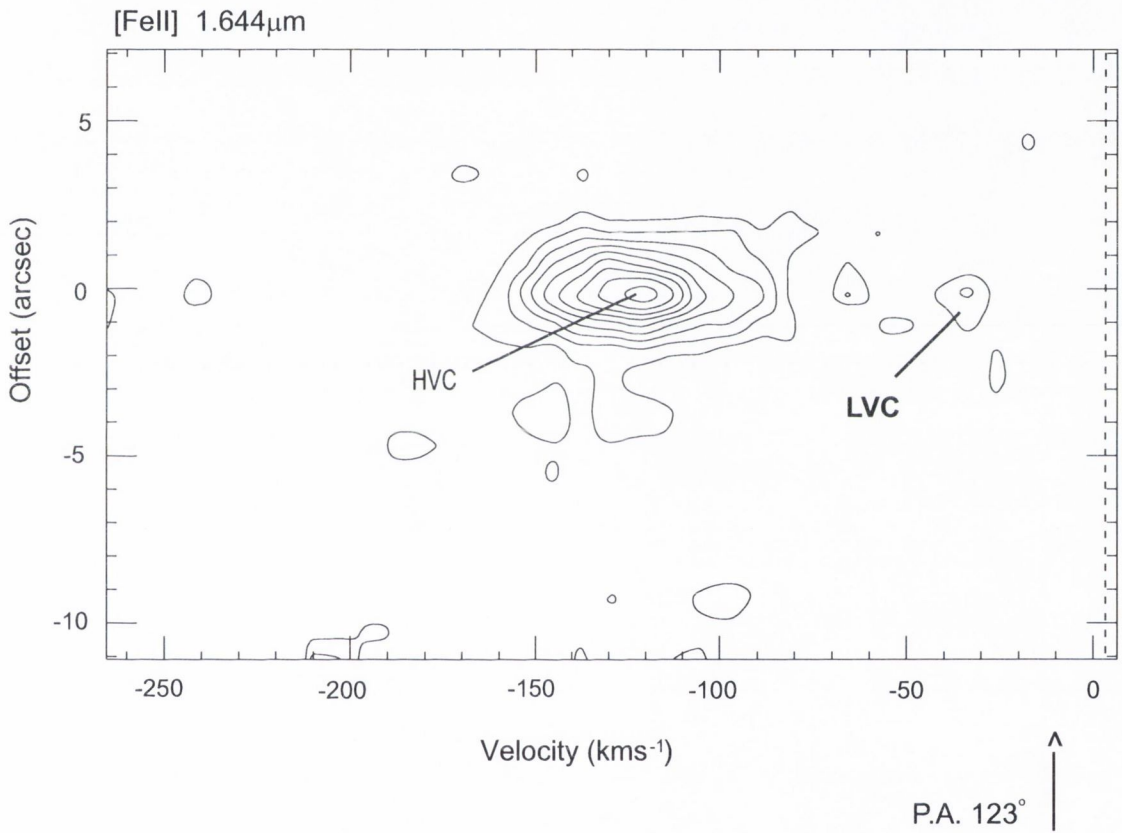


Figure 3.2: Continuum-subtracted position velocity diagrams of the [FeII] 1.644μm emission from SVS 13. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. The dashed lines mark the systemic velocity of the source. Velocities are with respect to the LSR.

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D are also associated with the outflow excited by this protostar (Reipurth et al., 1997). HH 300 A-C are located in the red-shifted counterflow about $30'$ southwest of the source and HH 300 D in the blue-shifted flow $\sim 40''$ to the northeast of the source. The systemic velocity of IRAS 04239+2436 is given at $+8 \text{ km s}^{-1}$ (Davis, Ray, Desroches, & Aspin, 2001).

The H_2 emission is confined to the source and peaks at a velocity of $\sim -10 \text{ km s}^{-1}$ (Davis, Ray, Desroches, & Aspin, 2001). I observe [FeII] $1.644\mu\text{m}$ emission from the $\sim 10''$ long jet and counter-jet at velocities of $-113 (\pm 5) \text{ km s}^{-1}$ and $+133 (\pm 5) \text{ km s}^{-1}$ respectively. Emission from the jet is strongest at a distance of $\sim 4''.5$ and the red-shifted flow peaks closer to the source at $\sim -1''.5$ (see Figures 3.3 and 3.7). The HH 300 D knot is also observed in [FeII] at $\sim 38''$.

3.2.3 L1551-IRS5

The L1551 dark molecular cloud is part of the Taurus-Auriga Cloud complex and, at a distance of $d \sim 140 \pm 10 \text{ pc}$ (Kenyon, Dobrzycka, & Hartmann, 1994) is one of the most studied regions of low-mass star formation. The infrared source L1551-IRS5 drives an extraordinary bipolar molecular outflow that is regarded as an archetype. The flow consists of a striking blue-shifted, wind swept cavity that extends over $10'$ (0.5 pc) to the southwest of IRS 5 (Stocke et al., 1988; Moriarty-Schieven & Snell, 1988) and is associated with an array of optical and near-IR shock features (Mundt & Fried, 1983; Davis, Mundt, Eisloffel, & Ray, 1995). This Class I YSO is also a binary but unlike SVS 13 both components are associated with circumstellar disks. It also appears that the source itself drives two small scale jets (Fridlund & Liseau, 1998; Hartigan et al., 2000; Itoh et al., 2000; Davis, Stern, Ray, & Chrysostomou, 2002). However, these jet like features may represent the edges of a single collimated flow (Mundt et al., 1991; Pyo et al., 2002). Indeed, the new images of Pyo et al. (2002) represent perhaps the strongest evidence yet that the two “jets” are simply the limb-brightened edges of a small, ovoidal cavity, that is bounded at its leading edge by a bright bow which they label PHK 3. (Rodríguez et al., 1998).

Pyo et al. (2002) also present a medium resolution echelle spectrum of the [FeII] $1.644 \mu\text{m}$ from this source. Two prominent velocity components are clearly evident. The first at $\sim -100 \text{ km s}^{-1}$ and a higher velocity component at $\sim -300 \text{ km s}^{-1}$. The line profile also shows pedestal and red-wing features. The authors interpret this result in terms of the model of Kwan (1997) and suggest that the pedestal

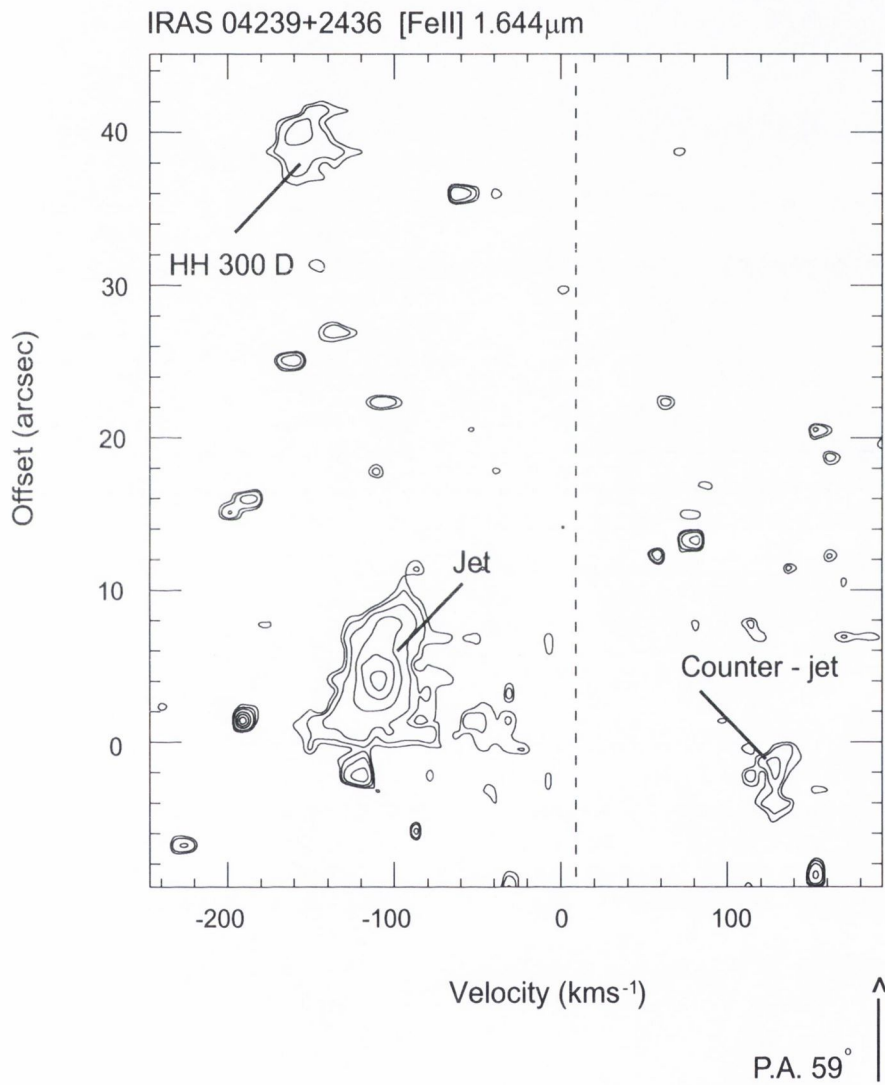


Figure 3.3: Continuum-subtracted position velocity diagrams of the [FeII] 1.644 μ m emission from IRAS 04239+2436. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. The dashed line marks the systemic velocity of the source. All velocities are with respect to the LSR.

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and red-wing features may represent gas from the lower velocity flow that has become entrained and accelerated by the very fast jet. Davis, Ray, Desroches, & Aspin (2001) detected complex velocity structure along the L1551-IRS5 jet in H_2 . Molecular hydrogen emission was detected from the blue and red-shifted lobes. At the source primarily low velocity emission at $\sim -7 \text{ km s}^{-1}$ is observed however the emission line profile has a small bump in the blue-wing which is representative of the high velocity jet. Moriarty-Schieven & Snell (1988) give the systemic velocity of this star at $\sim +6 \text{ km s}^{-1}$.

High velocity [FeII] emission is detected close to the exciting source and in the extended flow. Results are very similar to those of Pyo et al. (2002). Emission at the source is double peaked but instead of high and low velocity components the ELR is separated into a HVC at $\sim -120 (\pm 5) \text{ km s}^{-1}$ and an extremely high velocity component (EHVC) at $\sim -285 (\pm 15) \text{ km s}^{-1}$. The continuum subtracted position velocity diagram of the [FeII] ELR is shown in Figure 3.4. Spectro-astrometry (Figure 3.7) easily spatially resolves the two velocity components. The EHVC is offset to $-2''.5$ and the HVC to $-1''.25$. Compact [FeII] peaks are also detected further downwind at offsets of $\sim 12''$ and $\sim 23''$. The knot at $12''$ coincides with the optical/[FeII] bow shock PHK 3, labelled knot D by Fridlund & Liseau (1998).

3.2.4 HH 34-IRS

The archetypal HH 34 jet in L 1641 in Orion ($d \sim 450 \text{ pc}$) is only part of a giant parsec-scale outflow that includes HH 33, HH 34 N, HH 40 and HH 85 to the north and HH34S, HH 86-88 to the south (Devine et al., 1997a). This outflow was one of the first reported parsec-scale HH outflows and has a total known length of $\geq 3 \text{ pc}$. The source itself HH 34 IRS is embedded in a roughly 0.4 pc molecular core and has a luminosity of $\sim 45 L_\star$ (Rodríguez & Reipurth, 1996). The knotty HH 34 optical jet located $\sim 100''$ from HH34 IRS and extending for $\sim 30''$ back towards the source is probably the best known feature of this outflow (see Chapter 1 Figure 1.8). The jet consists of a periodic chain of HH knots of increasing separation, labelled A to L and these knots, or working surfaces, are perfect illustrations of HH shocks (Bührke et al., 1988). It is also highly collimated as the optical emission is confined to within a width of less than $1''$ (Ray et al., 1996; Reipurth et al., 2000). Eisloffel & Mundt (1992) studied the proper motions of the internal working surfaces of the HH 34 jet. The HH 34 bow shock, Mach disk and the optical jet are further discussed in

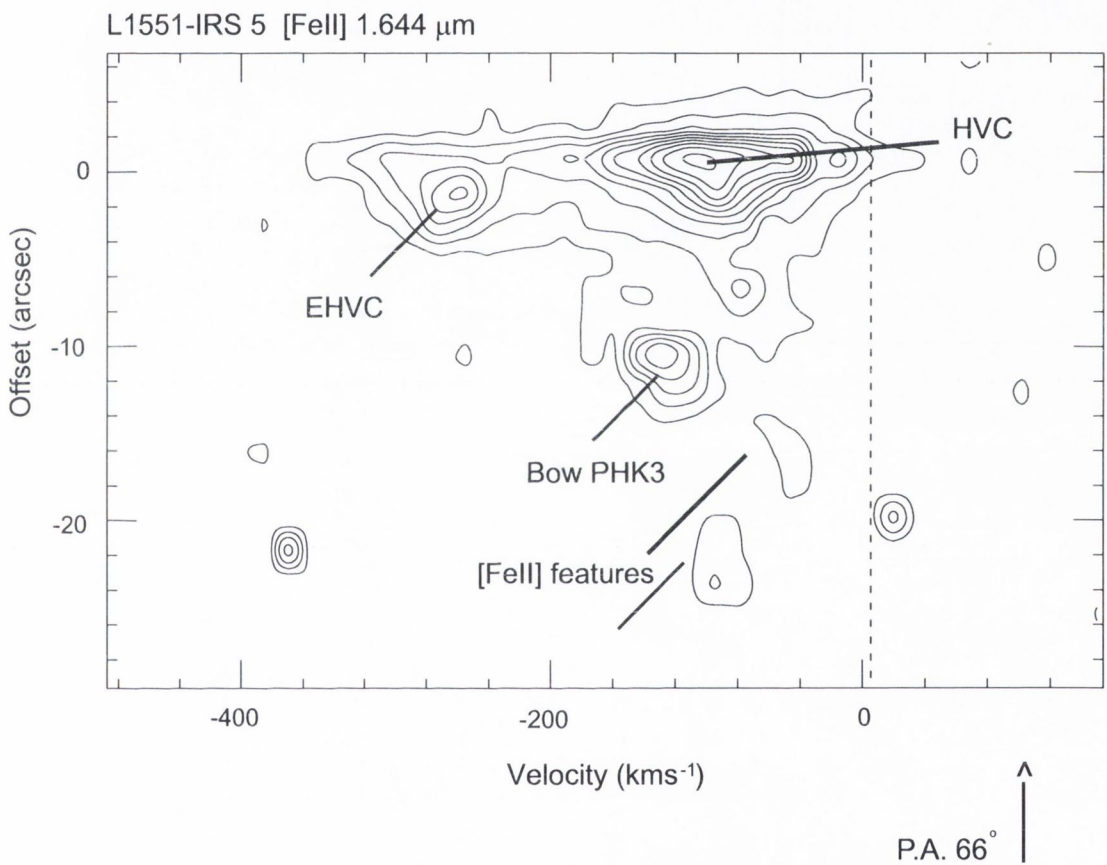


Figure 3.4: Continuum-subtracted position velocity diagrams of the [FeII] $1.644\mu\text{m}$ emission from L1551-IRS5. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. The dashed line marks the systemic velocity of the source. All velocities are with respect to the LSR.

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Chapter 1.

Davis, Ray, Desroches, & Aspin (2001) studied the MHELRL associated with HH 34. H₂ emission features were detected towards the source and along the blue-shifted optical jet. Knots C, I-J and L are clearly detected. The H₂ emission at the source has only one component a LVC at $\sim -24 (\pm 12)$ km s⁻¹. I observed [FeII] 1.644 μ m emission from knots E-F, H-I and J. The [FeII] emission in the jet is blue-shifted to ~ -120 km s⁻¹. At the source the [FeII] profile comprises a HVC at $\sim -95 (\pm 10)$ km s⁻¹ and a broad red-wing that extends back almost to the systemic rest velocity of $\sim +8$ km s⁻¹ Chernin & Masson (1995). The spectro-astrometric technique was not applied to the [FeII] ELR of HH 34 as only a very weak continuum is observed. Figure 3.5 is the position velocity diagram of the [FeII] ELR.

3.2.5 HH 379-IRS

HH 379 is situated in Cygnus near the molecular cloud 093.5-04.3 at a distance of ~ 0.9 kpc (Dobashi et al., 1994). This source may be associated with a nearby compact optical nebula (Devine et al., 1997b). Davis, Ray, Desroches, & Aspin (2001) assumed that this conical nebula harbours the exciting source of HH 379 and therefore positioned the spectrograph slit through the nebula and HH object. No continuum emission and only weak H₂ emission towards the assumed source position was observed. The H₂ emission close to the source was centred at the systemic velocity of the parent cloud ($\sim +3.5$ km s⁻¹). Similarly no continuum emission was observed in the vicinity of the [FeII] 1.644 μ m line, however the [FeII] ELR is strong towards the nominal source position. The [FeII] also peaks near the systemic rest velocity. The position velocity diagram of the [FeII] ELR is presented in Figure 3.6. Again as there is no continuum emission it was not possible to study the spatial properties of this ELR with respect to the source, using spectro-astrometry.

3.3 Discussion and Conclusions

Comparing [FeII] 1.644 μ m emission in a sample of Class I YSOs to, firstly, H₂ observations of the same sources and, secondly, to what is known for the CTTSs in [SII] $\lambda\lambda 6716, 6731$ say, is a simple exercise but an important one. Its importance relates to the fact that such a study answers questions regarding the spatio-kinematic

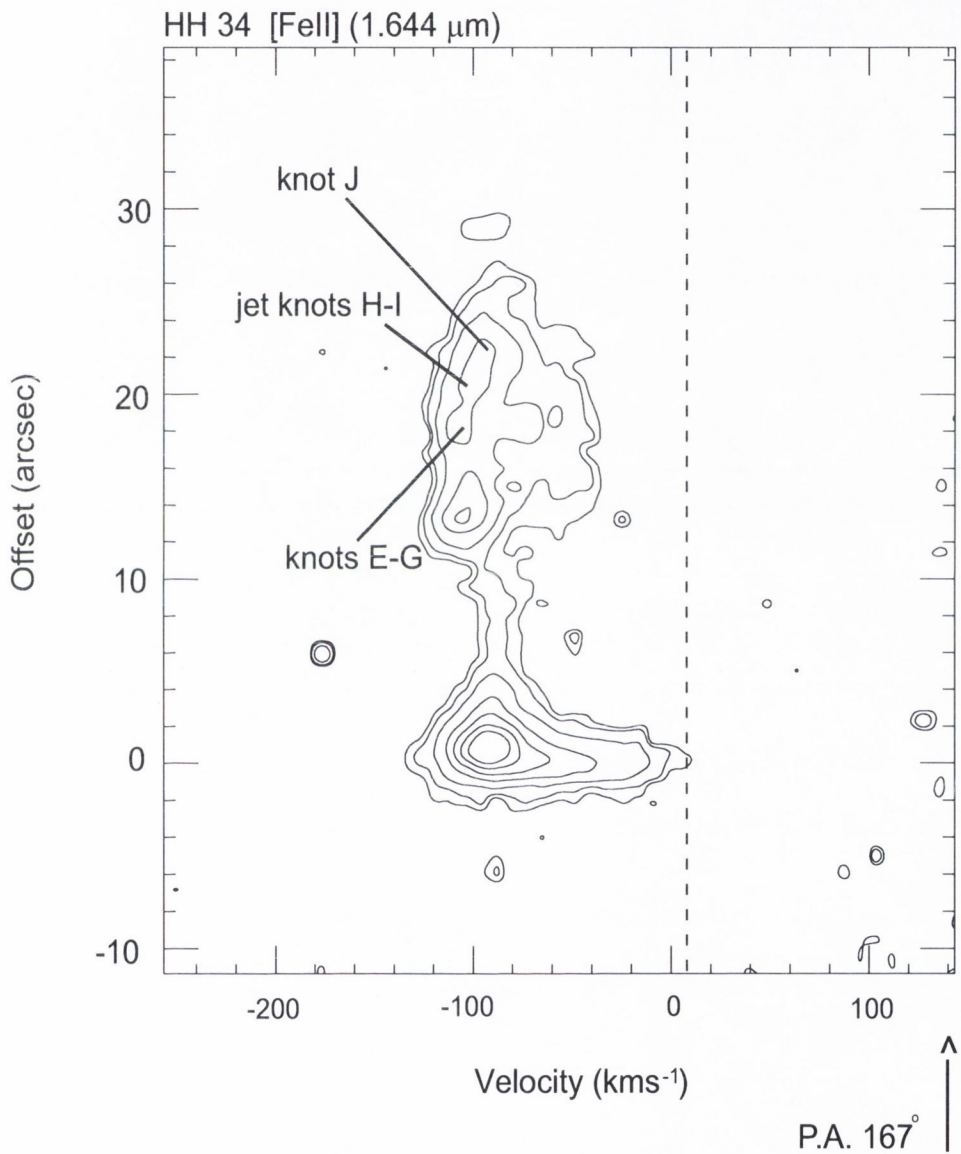


Figure 3.5: Continuum-subtracted position velocity diagram of the [FeII] $1.644\mu\text{m}$ emission from HH 34. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. The dashed line marks the systemic velocity of the source.

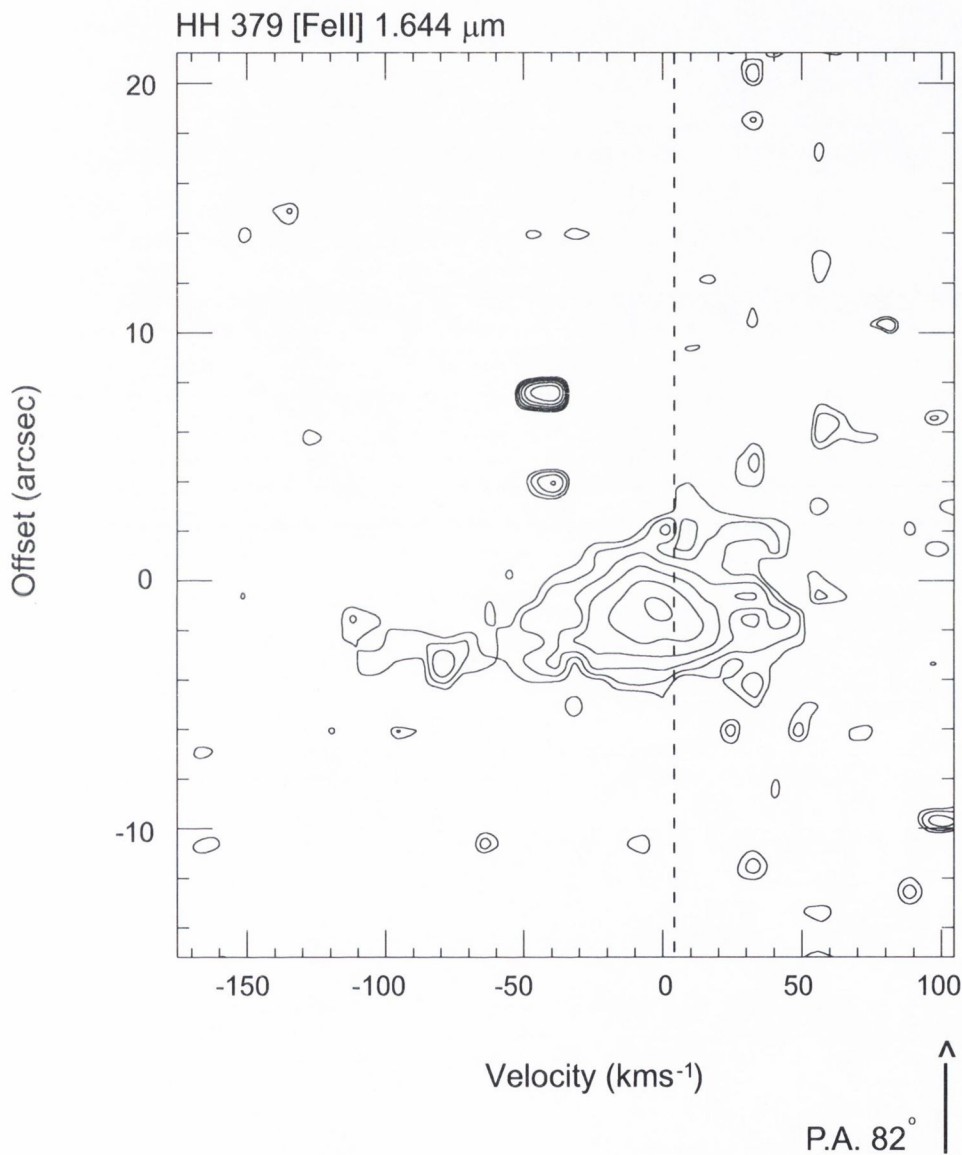


Figure 3.6: Continuum-subtracted position velocity diagram of the [FeII] 1.644 μm emission from HH 379. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. The dashed line marks the systemic velocity of the source.

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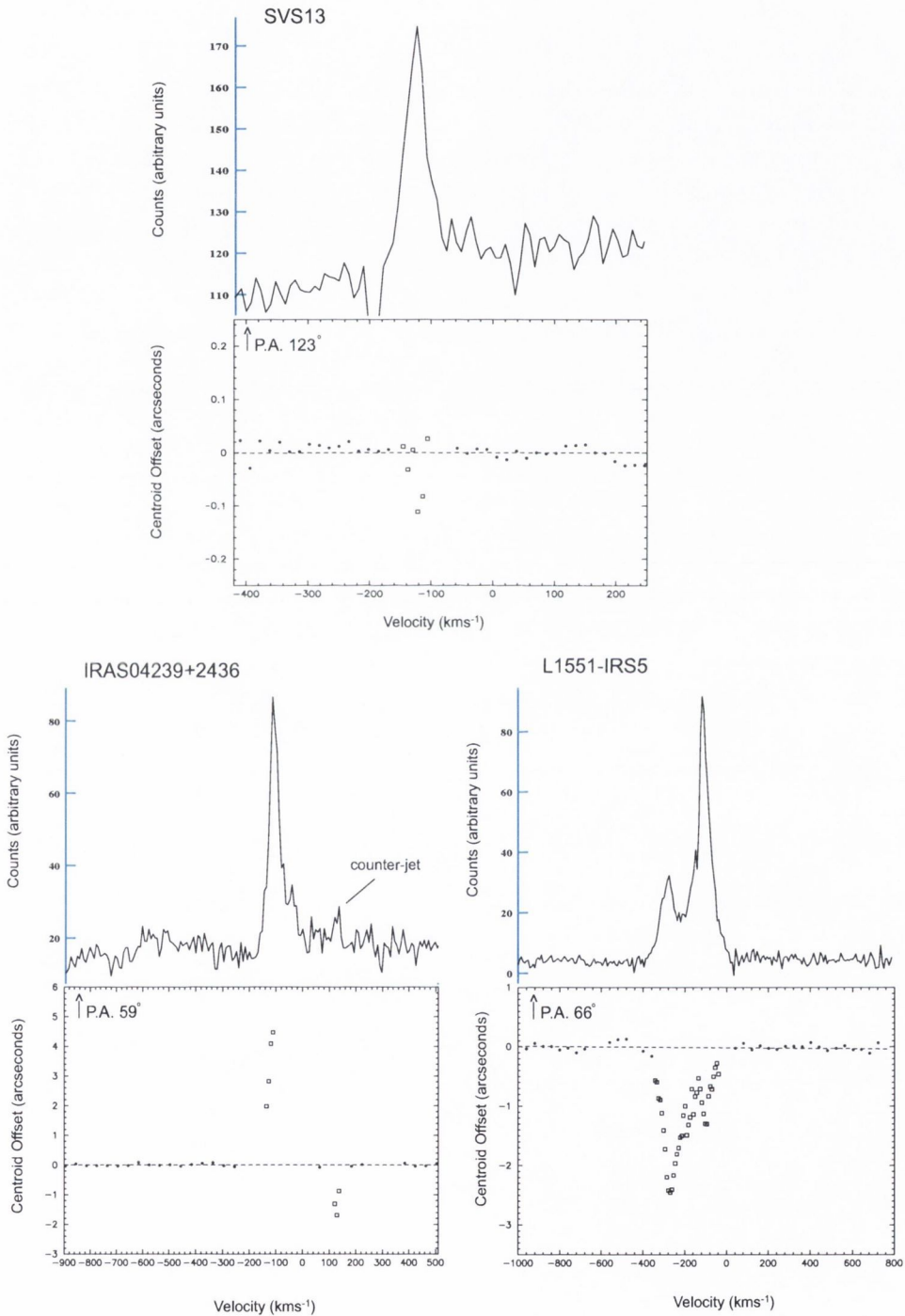


Figure 3.7: Offsets of the [FeII] emission peaks from the stellar continuum centroid and corresponding emission line profiles. The points at high red and blue-shifted velocities are measures of the continuum position. The dashed line in each plot is a polynomial fit to these continuum points.

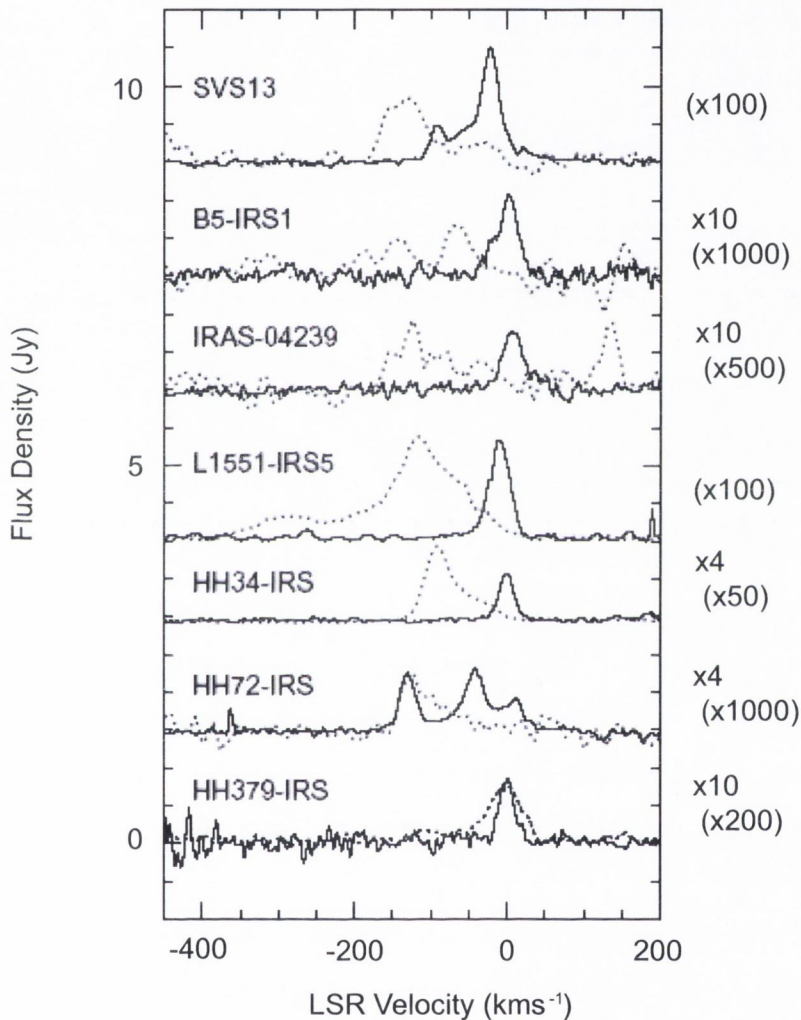


Figure 3.8: A comparison of the [FeII] and H_2 spectra extracted from the source continuum position in each target (the H_2 and [FeII] spectra represent the same 3-row wide area on each source). This figure is taken from Davis et al. (2003). H_2 spectra are drawn with full lines; [FeII] data with thick, dotted lines. The spectra have been multiplied by the values shown to the right of each plot (H_2 multiplication factor is unbracketted; [FeII] factor is bracketted). A constant has also been added to each plot so that all the data can be included in the same figure. B5 and HH 72 are not discussed here.

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properties of outflows launched from embedded Class I sources, close to their driving source. From the results above I can conclude that [FeII] $1.644\mu\text{m}$ is a very useful probe of outflows from low mass Class I sources. It is also clear that conditions in the jet launch region of Class I YSOs are similar to what has been well documented for the CTTSs. This is something that we cannot assume a priori. The following points are important to note:

1. The [FeII] observations reported in this chapter have kinematic and spatial characteristics that are very similar to [SII] $\lambda\lambda 6716, 6731$ observations of jets from CTTS. Both high and low velocity emission is observed and in all cases high velocity emission is displaced to a greater extent with respect to the position of the driving source than the low velocity emission. Figure 3.7 presents the spectro-astrometric plots of the [FeII] emission from SVS 13, L1551-IRS5 and IRAS04239+2436. All of these sources had strong continuum emission hence it was a straightforward process to accurately measure the centre of the continuum emission or position of the source. Both SVS 13 and L1551-IRS5 had multiple velocity components. SVS 13 had only very weak low velocity emission hence it was not possible to estimate its position however the presence of this emission at $\sim -20 \text{ kms}^{-1}$ attests to presence of a disk wind from this YSO.

L1551-IRS5 is different as although the [FeII] ELR is nicely separated in velocity and indeed position into two components (refer to Figures 3.4 and 3.7), the velocities of these components are much higher than what is generally measured for the CTTSs. The two components in the [FeII] $1.644\mu\text{m}$ spectrum of L1551-IRS5 are classified as a HVC and an EHVC rather than a LVC and a HVC. It is very clear from Figure 3.7 that the “extremely” high velocity emission from L1551-IRS5 is displaced further than the high velocity. For IRAS04239+2436 emission is located at $> 1''$ from the source position in both the blue and red-shifted outflow.

2. For both SVS 13 and L1551-IRS5 there is an initial increase in the displacement of emission with velocity. This is a trend also seen in the CTTSs and Takami et al. (2001) suggest that this points to an acceleration in the flow with distance, supporting magnetically driven wind models that predict such an acceleration (Decamp, 1981; Lago, 1984). These models deal with much

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smaller scales than are being probed in this study or by Takami et al. (2001). They model acceleration on scales of $\leq 10 R_*$ while spectro-astrometry is typically used to record offsets of ≥ 100 mas or ~ 15 AU. One has to be careful in interpreting this pattern of displacement in terms of acceleration as all that can really be inferred from this trend is that the same outflow mechanism is being reflected in each line. For IRAS 04239+2436 however there is a decrease in offset with velocity, especially in the blue-shifted lobe.

3. The multiple velocity components detected in the spectrum of L1551-IRS5 are spatially separated attesting to their separate origins. As discussed in Chapter 1, spectro-astrometry has been used previously to confirm the idea that the different components found in the FEL spectra of CTTs form in regions of differing density and temperature, thus favoring the model of Kwan (1997). [FeII] is emitted from a region similar in density to where H_2 originates but with a much higher temperature.

Overall [FeII] $1.644\mu\text{m}$ is a better tracer of higher velocity emission than H_2 so that the LVC is mainly seen in H_2 and the HVC in [FeII]. SVS 13 is a good illustration of this. Both low and high velocity emission is observed in both lines however the HVC dominated in [FeII] and the LVC in H_2 . Figure 3.8 illustrates this comparison. In IRAS 04239+2436, L1551-IRS5 and HH 34 an LVC is observed in H_2 that is not seen in [FeII] $1.644\mu\text{m}$.

4. L1551-IRS5 is an intriguing source. The comparison between the [FeII] $1.644\mu\text{m}$ and H_2 observations of this YSO reveal three velocity components, a LVC at $\sim -7 \text{ km s}^{-1}$ in H_2 , a HVC at $\sim -120 \text{ km s}^{-1}$ in [FeII] and a EHVC at $\sim -285 \text{ km s}^{-1}$ also in [FeII]. It is possible that what is being seen here is an example of entrainment. Basically the LVC represents the slow disk wind, the EHVC a very fast jet, and the HVC material from the disk wind which has become entrained and thus accelerated by the jet (Pyo et al., 2002).

Overall results suggest that the [FeII] emission derives from the base of a collimated, high velocity jet which entrains ambient molecular gas within a few hundred AU of each HH energy source. The low velocity disk wind and entrained gas is seen in H_2 emission.

Chapter 4

Paschen beta as a Tracer of Outflow Activity from Classical T Tauri stars, as Compared to Optical Forbidden Emission

Introduction

It is well established that FELs serve as powerful tracers of outflow activity close to the central engines of YSOs. Atomic hydrogen emission lines are also useful as a means of probing activity in the same region. In particular strong hydrogen emission lines are a hallmark feature of CTTs and their profiles are strongly influenced by the dynamics of the regions in which they form. In contrast to FELs, however, there is no consensus on how or where they are excited. Explanations based on their formation in outflows (Natta, Giovanardi, & Palla, 1988; Hartmann & Kenyon, 1990; Calvet & Hartmann, 1992) and in accretion zones as described by the magnetospheric accretion model (MAM) (Calvet & Hartmann, 1992; Hartmann, Hewett, & Calvet, 1994; Muzerolle, Calvet, & Hartmann, 1998a), have both been suggested. It seems likely that no model based solely on a mass loss or mass accretion scenario can account for all the different H I emission lines detected.

To date most work has been done using the Balmer lines, especially $H\alpha$. Although $H\alpha$ can form in outflows, at tens of AU from the source say, closer still the situation may be different (Calvet, 1997). For example, while P-Cygni $H\alpha$ profiles

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are clearly formed by winds it is obvious from studying inverse P-Cygni profiles that the $\text{H}\alpha$ line can be shaped by accretion. For profiles that are not P-Cygni in shape, however, questions still remain as to their origin. As reviewed in Chapter 2, Takami et al. (2001) and Takami, Bailey, & Chrysostomou (2003) demonstrated using spectro-astrometry that $\text{H}\alpha$ emission excited close to the driving sources of jets, assumed to trace only accretion, can also have an outflow component. Recent studies have shown that the MAM cannot entirely explain HI emission lines from, for example, the Brackett or Paschen series also. An important study by Folha & Emerson (2001) looked at the $\text{Pa}\beta$ line profiles of 49 T-Tauri stars and highlighted the differences found between predictions made by models and observations. They concluded that $\text{Pa}\beta$ emission may partly trace the outflow and that current models do not go far enough in accounting for the formation and characteristics of these lines. The work of Folha & Emerson (2001) is reviewed in more depth in section 4.3.2. Alencar & Basri (2000) also conclude from their study of permitted emission lines from T-Tauri stars that magnetospheric accretion is only part of the process that produces strong permitted emission in CTTs and that winds may have a role to play.

The main approach of this work is to compare results obtained from a study of a small sample of CTTs in $\text{Pa}\beta$ with optical FEL observations. In some cases $[\text{FeII}]$ 1.644 μm data is also used as a comparison, as two of the sources were observed in $[\text{FeII}]$, in addition to the Class I sources discussed in Chapter 3. My aim is to investigate if $\text{Pa}\beta$ is an effective tracer of outflows. If $\text{Pa}\beta$ can be used to study outflow activity from T-Tauri stars on small spatial scales then we have conclusive evidence that any explanation of the formation of HI lines based entirely on magnetospheric accretion is flawed. Also this will make $\text{Pa}\beta$ a very important line for use in conjunction with the new class of near-infrared interferometers, for example AMBER, now coming online (Richichi, Malbet, Hofmann, & Petrov, 2000). They will give very high spatial resolution making $\text{Pa}\beta$ a strong probe of the central engine, especially when combined with spectro-astrometry.

4.1 Observations/Data Reduction

Near-infrared $\text{Pa}\beta$ observations were acquired for the four CTTs listed in Table 4.1. These observations were complemented by optical forbidden emission line data.

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Source	RA (J2000)	Dec (J2000)	Slit P.A.
DG Tau	04 27 04.7	+26 06 17	46°
V536 Aql	19 38 57	+10 30 16.6	110°
LkH α 321	21 01 55.1	+49 51 35	208°
RW Aur	05 07 49.6	+30 24 05	125°

Table 4.1: Right Ascension, Declination and Position Angle (P.A.) of all sources included in this study.

However only 3 out of 4 of the sources were observed in the optical, namely DG Tau, V536 Aql and LkH α 321. Observations taken during three different runs make up the data set.

Firstly the $\text{Pa}\beta$ observations of DG Tau and RW Aur were obtained at UKIRT on 3 November 2001 using the CGS4 spectrometer. The [FeII] data presented as a comparison for both these sources was also taken on this night. CGS4 is equipped with a 256×256 InSb array. The pixel scale at $1.2822\mu\text{m}$ and $1.644\mu\text{m}$ measures $0''.88$ in the spatial direction. The slit width was two pixels giving a velocity resolution of $\sim 7.5 \text{ kms}^{-1}$ and $\sim 8 \text{ kms}^{-1}$ per pixel for $\text{Pa}\beta$ and [FeII] respectively. The instrumental profile in the dispersion direction measured from gaussian fits to arc lines was $19.0(\pm 1.0 \text{ kms}^{-1})$. In each observation the slit was orientated so that the source was at the centre of the slit and along the jet axis. Position angles for each of the sources are shown in Table 4.1. Secondly the $\text{Pa}\beta$ observations of V536 Aql and LkH α 321 were made on 7 August 2002 during a service run on UKIRT. Again the CGS4 spectrometer was used and the slit width, pixel scale and dispersion were the same as for the November run.

In both cases a sequence comprising one sky followed by three object exposures was repeated a number of times for each source, in order to build up signal to noise. The sky position was typically $30''$ to $60''$ away from each source in a direction orthogonal to the outflow axis. Each image was bias subtracted, flatfielded and co-added into reduced groups. The data reduction was done using standard IRAF routines. In the case of the $\text{Pa}\beta$ observations each source was wavelength calibrated using a krypton argon arc that was obtained immediately prior to observing each spectrum. Only two arc lines, could be used for wavelength calibration. They were the krypton line at $\lambda_{vac} = 1.27859\mu\text{m}$ and the argon line at $\lambda_{vac} = 1.28062\mu\text{m}$. The [FeII] data was calibrated as described in Chapter 3.

The optical FEL data was taken during service runs on the INT using the IDS.

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Both DG Tau and LkH α 321 were observed on 17 September 2002 and V536 Aql on 10 October 2002. With the IDS the 500mm camera, the R1200Y grating and the EEV10 CCD chip were used. This gave a central wavelength of 6500Å, a pixel scale of 0".19 and an approximate dispersion of 0.22Å per pixel. The spectra from DG Tau and LkH α 321 were calibrated using a copper-argon arc spectrum. V536 Aql was calibrated using a copper-neon arc.

The absolute velocity calibration for all sources was checked by self-calibrating the arc spectrum. For the $\text{Pa}\beta$ data, variations in the calibration were found to be small, only of the order of 3 kms⁻¹. As reported in Chapter 3 the corresponding values for the [FeII] data were of the order of 5 kms⁻¹. In the case of the optical data the CuAr and CuNe arcs gave a variation of less than 1 kms⁻¹. Variations were much less towards the centre of the array. The seeing was measured for each observation and is given in Table B.1 in Appendix B.

4.2 Results

As stated above the main aim of this study is to directly compare optical FEL spectra (and in some cases [FeII] spectra) with $\text{Pa}\beta$ spectra. With this in mind the main results are presented in the form of spectro-astrometric plots, showing the relative position of the FEL and $\text{Pa}\beta$ emission with respect to the source continuum position. Spectro-astrometry will reveal displacements in the $\text{Pa}\beta$ ELRs, caused by the presence of an outflow component to the emission, which cannot be detected in a simple position velocity diagram. Continuum-subtracted position velocity diagrams were also prepared for the [OI] λ 6300 and [SII] λ 6731 ELRs in DG Tau and V536 Aql and the [SII] λ λ 6716,6731 ELRs, only in LkH α 321. All velocities quoted here are LSR velocities and the systemic velocities of V536 Aql and LkH α 321 are estimated using the photospheric Li λ 6708 absorption line. The accuracy of the spectro-astrometric measurements discussed here is estimated as outlined in Chapter 2 section 2.3. Errors remain constant across the continuum and the error in the continuum position for all the lines discussed here is found to be between 4 and 16 mas. The largest errors are recorded in the $\text{Pa}\beta$ line-wings and are between ~ 25 mas for V536 Aql and ~ 54 mas for DG Tau. Hence all offsets recorded in the $\text{Pa}\beta$ line-wings are $> 3\sigma$ detections. The average error estimated for the FELRs is 13 mas.

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4.2.1 DG Tau (HH 158)

DG Tau is one of the closest CTTSs stars at a distance of ~ 140 pc and it has been shown to drive a well-collimated HH jet (HH 158). It was amongst one of the first CTTSs from which a jet-like outflow was discovered (Mundt & Fried, 1983). The jet which has been well studied spectroscopically at optical forbidden emission lines, firstly at medium resolution (Mundt, Brugel, & Bührke, 1987) and later at high spatial and spectral resolution (Lavalley et al., 1997; Eislöffel & Mundt, 1998) extends to approximately $12''$ in a southwest direction. Eislöffel & Mundt (1998) detected four knot like features labelled A,B,C,D and suggested that the jet terminates in a bow shock at Knot C (refer to Figure 4.1). Lavalley et al. (1997) presented further data on two knots close to the star, i.e. Knots A and B mentioned above, and concluded that Knot B also had a velocity gradient and morphology consistent with it being a bow shock.

Solf & Böhm (1993) studied the optical forbidden emission from the jet close to the source i.e within $0''.5$ and found evidence for two separate gas components in the flow, a low and a high velocity component, following the model of Kwan & Tademaru (1988). A recent study by McGroarty & Ray (2004b) demonstrated that the DG Tau outflow is not just composed of the small-scale jet $12''$ in size but includes several other HH objects extending the size of the outflow to over 1 parsec. Lastly, further studies have been carried out with HST by Bacciotti et al. (2000) and Bacciotti et al. (2002), showing the jet structure to within a few tenths of an arcsecond of the source and measuring rotation in the jet.

Here the detection of the $\text{Pa}\beta$ emission line in the DG Tau spectrum is reported. It has a FWHM of $\sim 225 \text{ kms}^{-1}$, a blue-wing that extends to approximately -380 kms^{-1} and is centred at $V_{LSR} \sim +8 \text{ kms}^{-1}$. For DG Tau the systemic velocity is $+6 \text{ kms}^{-1}$ (Kitamura, Kawabe, & Saito, 1996). Figure 4.2 shows the result of applying the spectro-astrometric technique to the $\text{Pa}\beta$ ELR. An offset is measured in the blue-shifted wing out to about $0''.5$ from the source and the offset peaks at a velocity of $\sim -250 \text{ kms}^{-1}$. $[\text{FeII}] 1.644\mu\text{m}$ is also detected from the DG Tau jet, refer to Figures 4.3 and 4.4.

Optical long-slit spectroscopic observations show $[\text{OI}]\lambda\lambda 6300, 6363$, $[\text{NII}]\lambda\lambda 6548, 6583$, $\text{H}\alpha$ and $[\text{SII}]\lambda\lambda 6716, 6731$ emission. At the source, in $[\text{SII}]\lambda 6731$ a LVC at $-47 (\pm 7) \text{ kms}^{-1}$ and a some weak high velocity emission at $-240 (\pm 6) \text{ kms}^{-1}$ are present. The $[\text{OI}]\lambda 6300$ is clearly double peaked. The low velocity component has

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a centroid velocity of $\sim -47 \text{ kms}^{-1} (\pm 6) \text{ kms}^{-1}$ and the high velocity component peaks at $\sim -266 (\pm 6) \text{ kms}^{-1}$. Figure 4.1 presents the continuum subtracted position velocity diagrams for the $[\text{SII}]\lambda 6731$ and $[\text{OI}]\lambda 6300$ lines. Knots B and C mentioned above are seen. For both lines emission in the vicinity of the source (Knot A) is displaced in the same direction as emission in the $\text{Pa}\beta$ blue line-wing (see Figure 4.2). The maximum displacements recorded in both $[\text{SII}]\lambda 6731$ and $[\text{OI}]\lambda 6300$ ELRs are listed in Table 4.2. The $\text{H}\alpha$ emission line is double peaked with the secondary peak blue-shifted to a velocity of $\sim -290 \text{ kms}^{-1}$ and displaced to $\sim 0''.37$. This corresponds in velocity to the blue-wing of the $\text{Pa}\beta$ line and the $\text{H}\alpha$ secondary peak is displaced to a slightly smaller extent than the $\text{Pa}\beta$ wing (again refer to Figure 4.2). Also shown in the spectro-astrometric plot of the $\text{H}\alpha$ line region are the $[\text{NII}]\lambda 6548$ and $[\text{NII}]\lambda 6583$ lines.

4.2.2 V536 Aql

Early studies of the Classical T-Tauri star V536 Aql showed it to have relatively strong forbidden line emission in $[\text{OI}]\lambda 6300$ (Cohen & Kuhi, 1979) and a large degree of polarisation (Bastien, 1982). Ageorges, Ménard, Monin, & Eckart (1994) presented the first evidence for an extended circumstellar medium around V536 Aql. They also presented in their paper high angular resolution images that showed for the first time that V536 Aql is a pre-main sequence binary. The two stars are separated by $0''.52$ at a PA of 17° . The spectroscopic study of Hirth, Mundt, & Solf (1997) provided the first conclusive observation of the bipolar outflow from V536 Aql. They studied it in various optical FELs and showed that it is spatially extended by about $3''\text{--}4''$ at a PA of $90^\circ \pm 20^\circ$ for the blue-shifted part of the flow. Lastly the $[\text{SII}]\lambda\lambda 6716, 6731$ and continuum images taken by Mundt & Eislöffel (1998) confirmed the findings of Hirth, Mundt, & Solf (1997). The images showed several knots at a position angle of 110° . The nearest of these was at about $4''.2$ and the furthest was located at about $16''$. In the $[\text{SII}]$ image a faint counterflow was seen.

V536 Aql was not one of the sources that formed part of the $[\text{FeII}]$ study but it was included in the service night observations on UKIRT. No $[\text{FeII}]$ emission is observed but a strong $\text{Pa}\beta$ ELR is. The $\text{Pa}\beta$ line has a FWHM of $\sim 167 \text{ kms}^{-1}$ centred at $\sim -30 (\pm 9) \text{ kms}^{-1}$ and a red-wing that extends to $\sim 300 \text{ kms}^{-1}$. Applying the spectro-astrometric technique to this source reveals offsets tracing both the red

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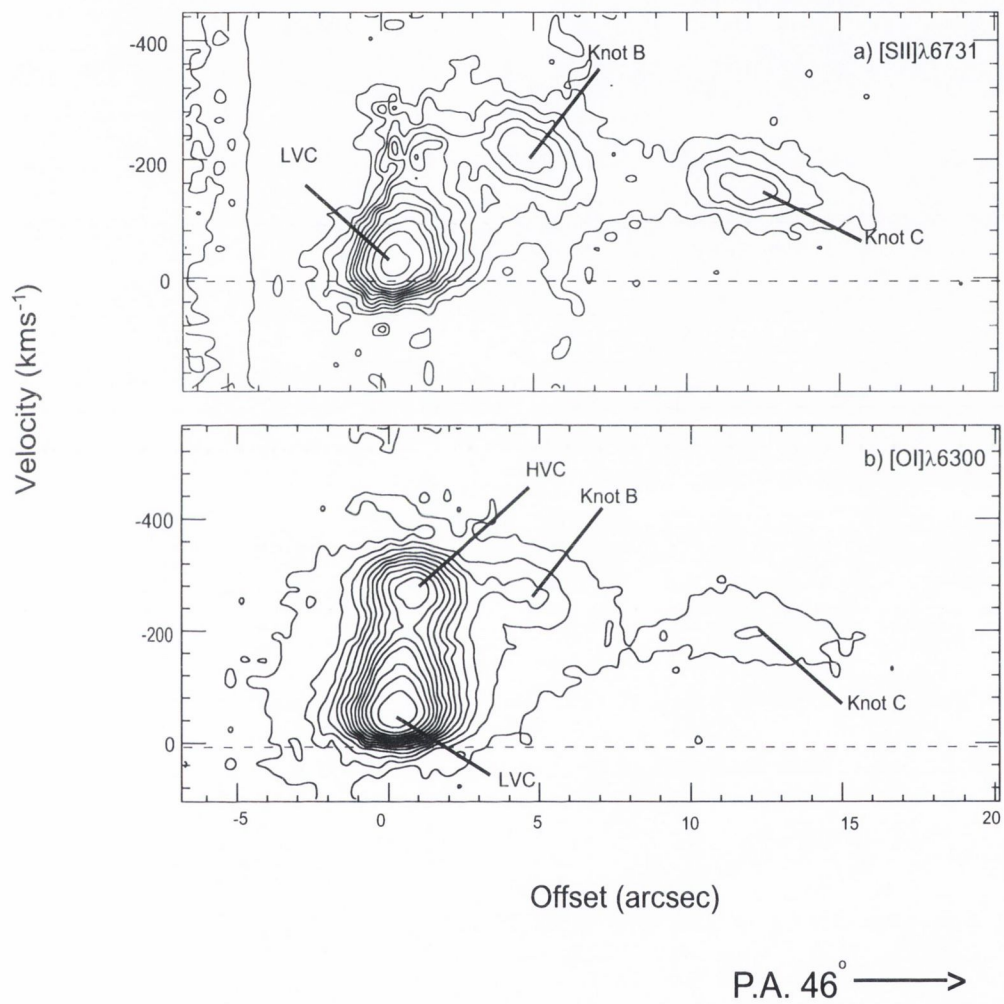


Figure 4.1: Continuum-subtracted position velocity diagrams of the optical forbidden emission lines from DG Tau. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. The dashed lines mark the systemic velocity of the source. All velocities are with respect to the LSR.

DG Tau

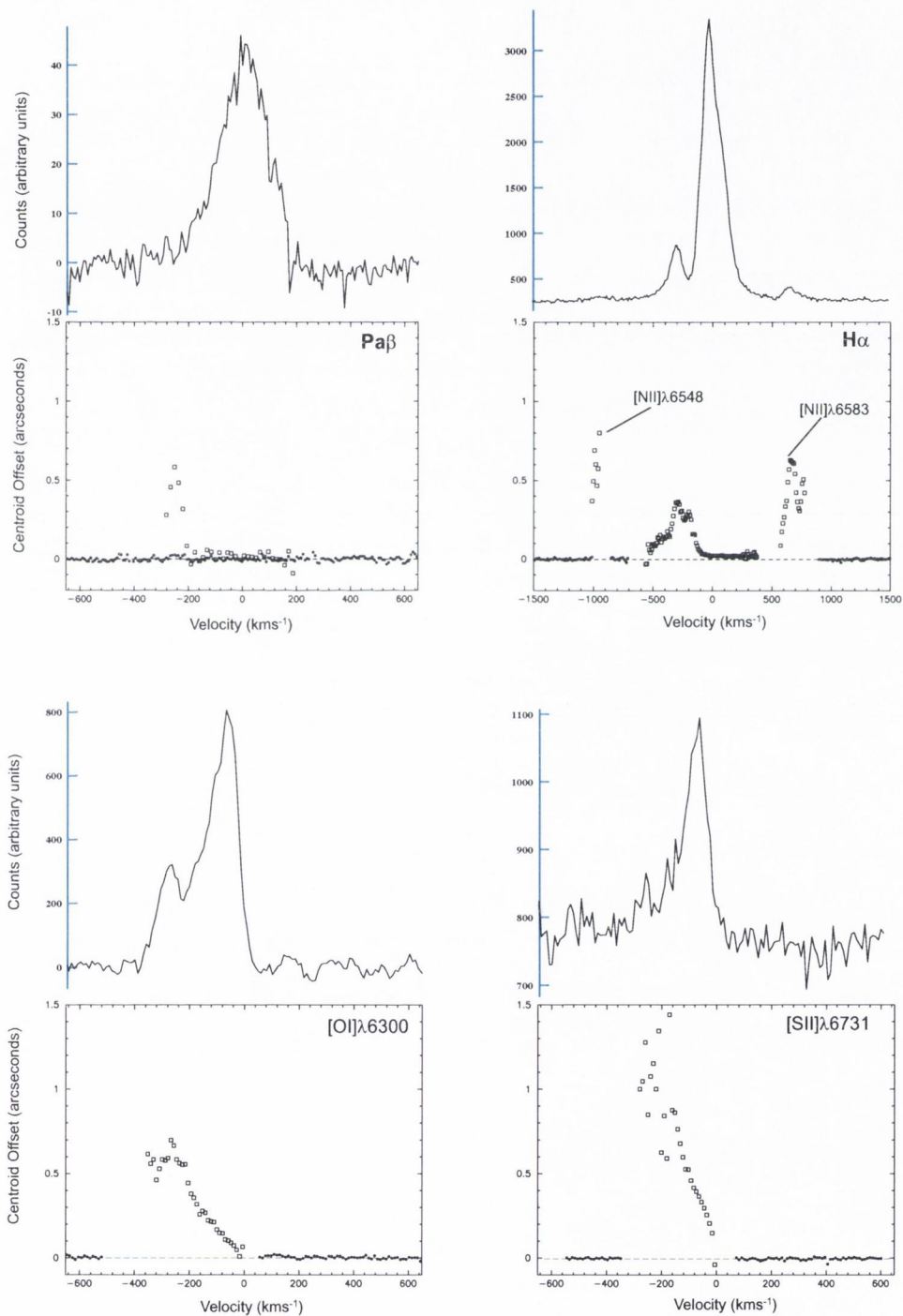


Figure 4.2: Emission line profiles and corresponding spectro-astrometric plots of the $\text{Pa}\beta$, $\text{H}\alpha$, $[\text{OI}]\lambda 6300$ and $[\text{SII}]\lambda 6731$ ELRs in the spectrum of DG Tau. The P.A. is 46° in the positive offset direction. The $[\text{NII}]\lambda 6548$ and $[\text{NII}]\lambda 6583$ lines are included in the $\text{H}\alpha$ plot.

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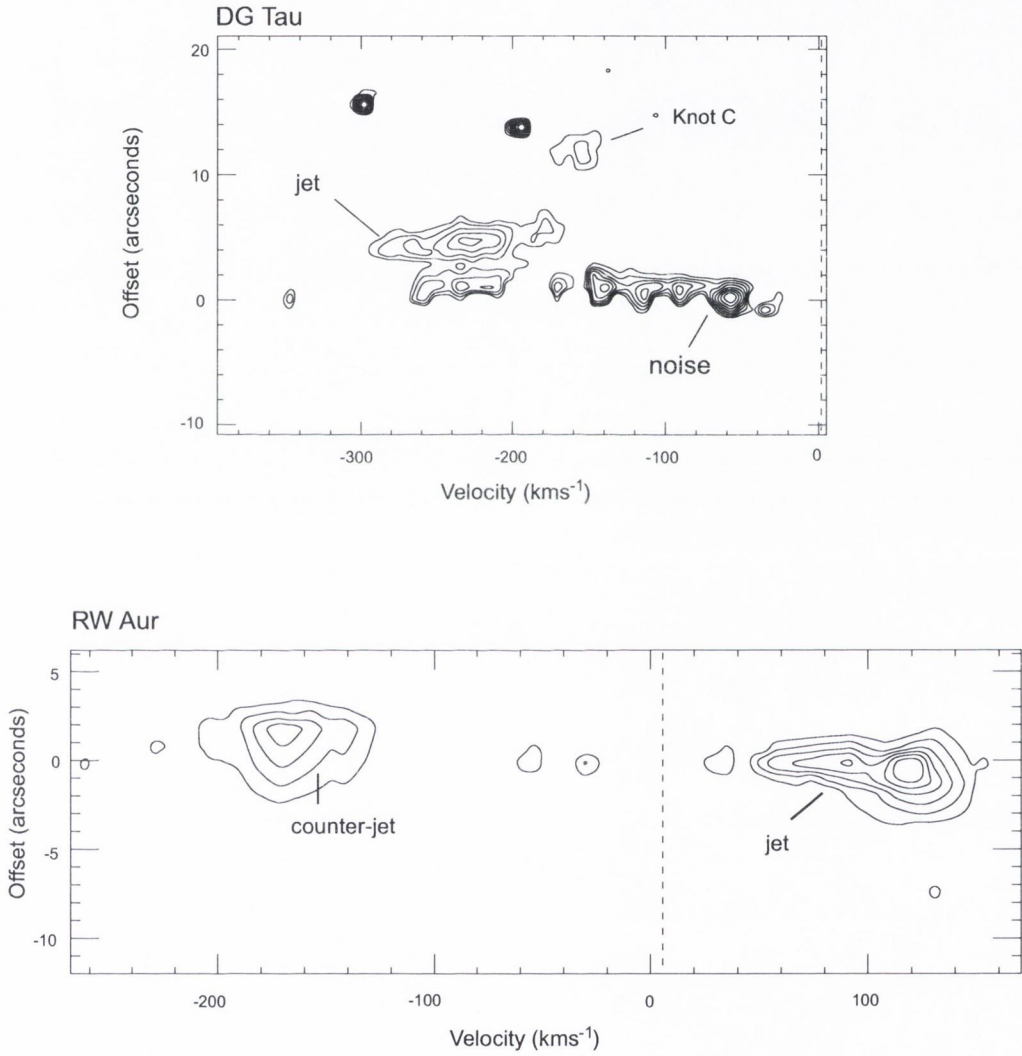


Figure 4.3: Continuum-subtracted position velocity diagrams of the $[\text{FeII}]$ $1.644\mu\text{m}$ emission from DG Tau and RW Aur. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. Knot C in the DG Tau flow is detected $\sim 12''$ from the source. For RW Aur both the jet and counter-jet are detected in $[\text{FeII}]$. The dashed lines mark the systemic velocity of the sources. All velocities are with respect to the LSR.

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and blue lobes of the flow, see Figure 4.6. The blue-wing is displaced to $\sim 0''.1$ and the red-wing to $\sim -0''.085$. I estimate the systemic velocity of this source at approximately -2 km s^{-1} .

FEL observations V536 Aql in the optical gave the following results. I detected $[\text{OI}]\lambda\lambda 6300, 6363$, $[\text{NII}]\lambda\lambda 6548, 6583$ and the $[\text{SII}]\lambda\lambda 6716, 6731$ emission from the extended outflow but only out to about $3''$. The $[\text{SII}]\lambda 6731$ and $[\text{OI}]\lambda 6300$ lines made up the strongest emission close to the source. In the case of $[\text{SII}]\lambda 6731$ the line profile is made up of a LVC at $-20 (\pm 5) \text{ km s}^{-1}$ and some weak high velocity emission at $-84 (\pm 5) \text{ km s}^{-1}$. Hirth, Mundt, & Solf (1997) report the $[\text{OI}]\lambda 6300$ emission line as being double peaked with a LVC at -7 km s^{-1} and a HVC at -77 km s^{-1} (data was taken in November 1993). I observed a strong LVC at $\sim -10 (\pm 7) \text{ km s}^{-1}$ and a blended HVC which is estimated to be at $\sim -65 \text{ km s}^{-1}$. Position velocity diagrams for the $[\text{SII}]\lambda 6731$ and $[\text{OI}]\lambda 6300$ emission were again prepared (see Figure 4.5). Refer to Table 4.2 for the displacements measured in the optical FELRs. Interestingly the $\text{H}\alpha$ emission from this star has a similar profile to the $\text{Pa}\beta$ profile. It has FWHM of 200 km s^{-1} , is centred at $\sim -7 (\pm 9) \text{ km s}^{-1}$ and it has symmetric red and blue-wings that extend to approximately -300 km s^{-1} . Again spectro-astrometry reveals a displacement in both the red and blue-wings of $0''.065$ and $-0''.04$ respectively. The results of the spectro-astrometry of all the ELRs are given in Figure 4.6 and the $[\text{NII}]\lambda 6548$ and $[\text{NII}]\lambda 6583$ lines are included in the $\text{H}\alpha$ spectro-astrometric plot.

4.2.3 LkH α 321

This YSO has been little studied to date. Mundt & Eislöffel (1998) classify it as a CTTS, however Herbst & Shevchenko (1999) describe it as being an intermediate mass YSO. Indeed the luminosity and mass of this source ($146L_{\odot}$, $3M_{\odot}$, Chavarria 1981) would certainly place it in the intermediate mass category. The distance of its parent cloud has been estimated at $\sim 550 \text{ pc}$ (Shevchenko, Yakulov, Hambarian, & Garibjanian, 1991). It was shown by Cohen & Kuhl (1979) to have FELs of only moderate strength. Mundt & Fried (1983) revealed that it had prominent blue-shifted absorption features in the $\text{NaI}\lambda\lambda 5890, 5896$ absorption lines. Mundt & Eislöffel (1998) published $[\text{SII}]\lambda\lambda 6716, 6731$ and continuum images. The $[\text{SII}]$ and the $[\text{SII}]$ -continuum images showed a knotty jet extending $22''$ to a very faint knot labelled Knot E at a PA of 208° . The only evidence for a counterflow is a faint

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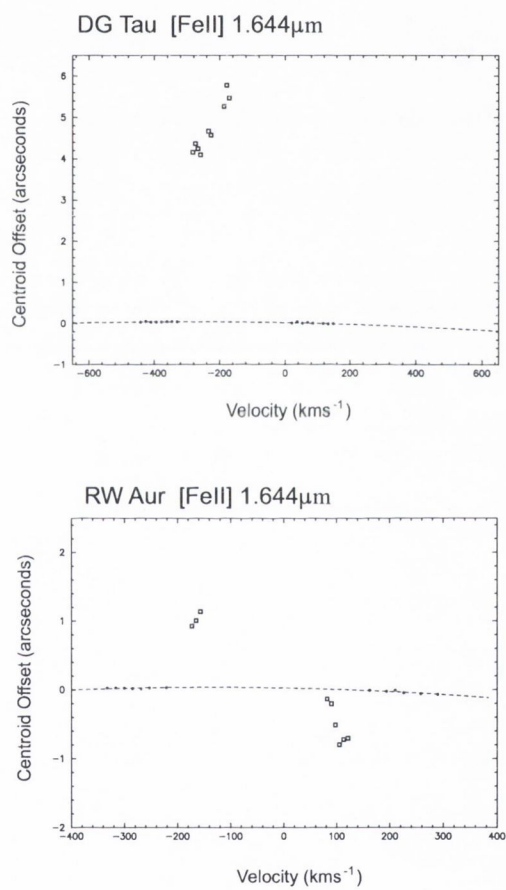


Figure 4.4: Spectro-astrometric plots of the $[\text{FeII}]$ $1.644\mu\text{m}$ ELRs close to DG Tau and RW Aur. All velocities are with respect to the LSR.

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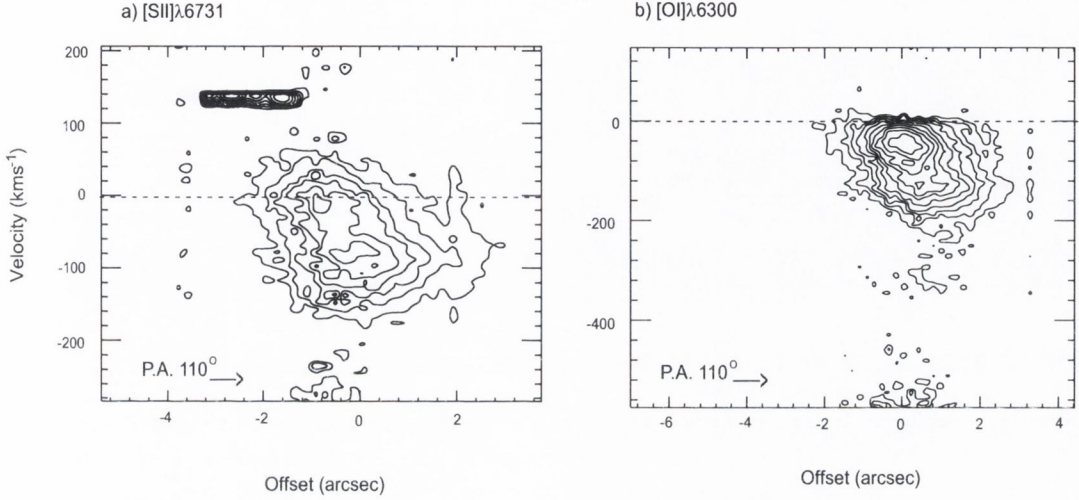


Figure 4.5: Continuum-subtracted position velocity diagrams of the optical forbidden emission lines from V536 Aql. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. The dashed lines mark the systemic velocity of the source. All velocities are with respect to the LSR.

knot labelled Knot F seen only in the [SII]-continuum image. Coffey et al. (2004) measure an anti-clockwise rotation at the base of the blue-shifted jet. The systemic velocity of this source with respect to the LSR is estimated to be $+\sim 9 \text{ km s}^{-1}$.

Again the near-infrared observations of this source were taken on UKIRT using CGS4 during a service run. The [FeII] emission from $\text{LkH}\alpha$ 321 is red-shifted and peaks at a LSR velocity of $229 (\pm 4) \text{ km s}^{-1}$. Unusually the blue-shifted flow is not seen in [FeII]. Either there is no blue-shifted emission or else it is blended with the strong Brackett 12 line ($1.641168 \mu\text{m}$). The red-shifted [FeII] was far too weak with respect to the continuum for any positional displacement to be measured. The $\text{Pa}\beta$ line profile is broad with a FWHM of approximately 300 km s^{-1} and is centred on $\sim -3 (\pm 10) \text{ km s}^{-1}$. Spectro-astrometry reveals offsets in emission tracing both red and blue-shifted outflowing material. In the blue-wing offsets peak at approximately 160 km s^{-1} and $0''.13$. The corresponding values for the red-wing are 120 km s^{-1} and $0''.075$.

Again optical observations of the source were made with the IDS on the INT. [SII] $\lambda\lambda 6716, 6731$, [NII] $\lambda 6583$, $\text{H}\alpha$ and [OI] $\lambda 6300$ emission is detected. The [SII] $\lambda 6731$ and the [OI] $\lambda 6300$ lines are the strongest FELs close to the source but in comparison to what is observed for DG Tau or V536 Aql the emission is very weak. This is especially apparent through a comparison of the position velocity diagrams

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V536 Aql

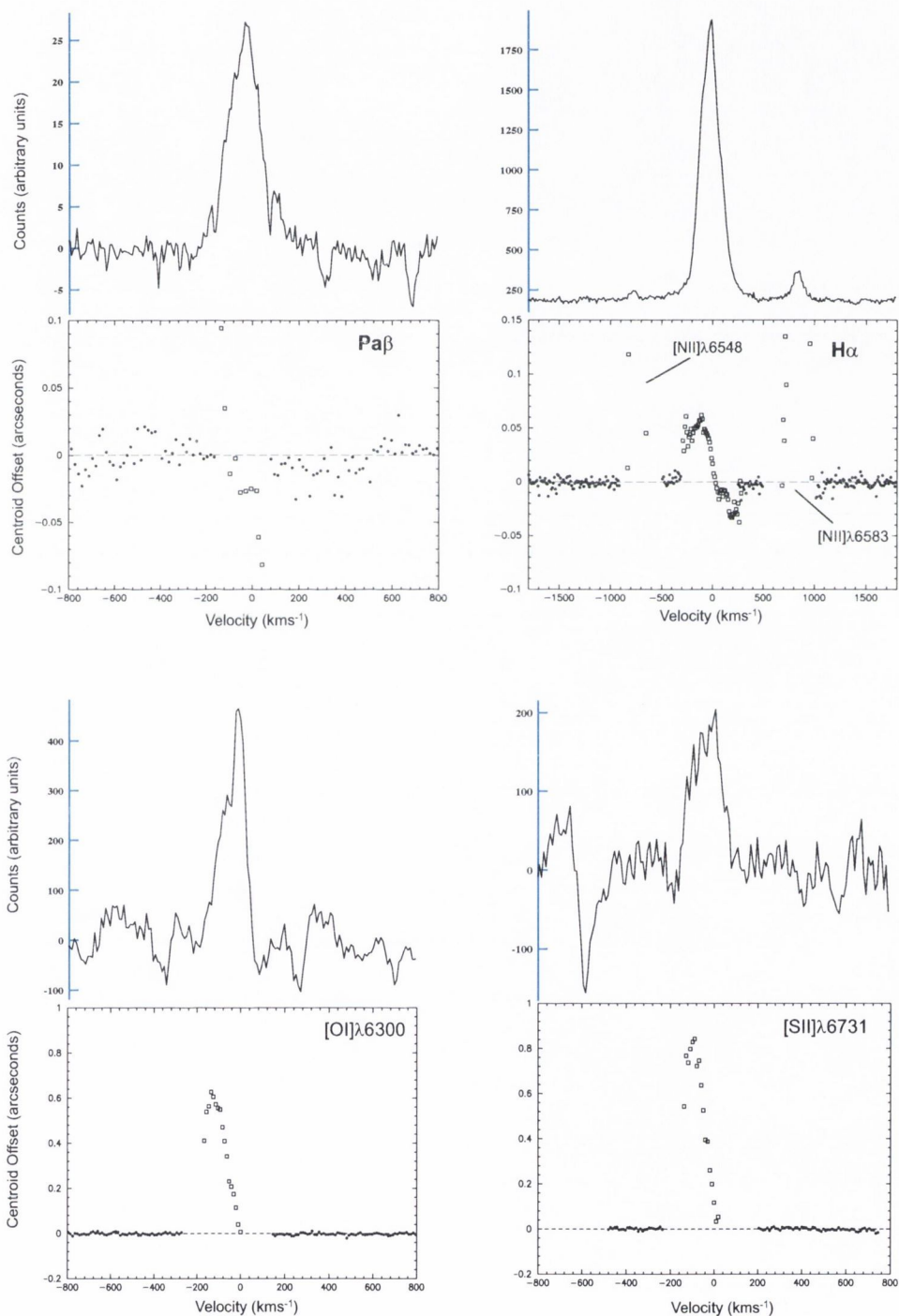


Figure 4.6: Emission line profiles and corresponding spectro-astrometric plots of the Pa β , H α , [OI] λ 6300 and [SII] λ 6731 ELRs in the spectrum of V536 Aql. The P.A. is 110° in the positive offset direction. The [NII] λ 6548 and [NII] λ 6583 lines are included in the H α plot. Emission in these line regions extends to $\sim 1.2''$.

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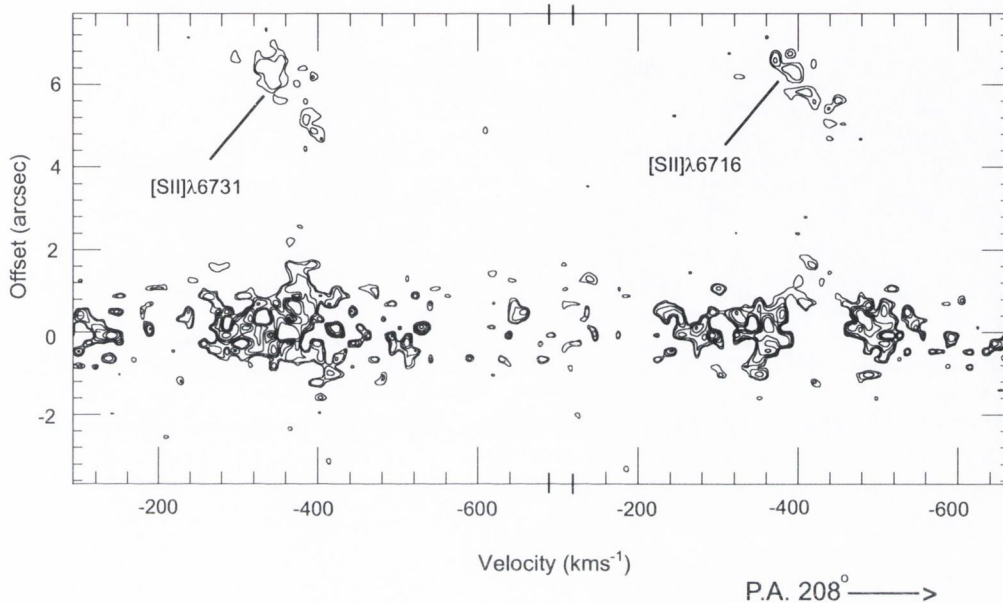


Figure 4.7: Continuum-subtracted position velocity diagram of the $[\text{SII}]\lambda\lambda 6716, 6731$ ELRs at LkH α 321. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. The systemic velocity of this star is measured at $+9 \text{ km s}^{-1}$. Emission at the source is weak relative to the other CTTSs studied and there are also weak $[\text{SII}]$ knots at $\sim 7''$.

of the $[\text{SII}]\lambda 6731$ ELRs of the three sources. The position velocity diagrams of the $[\text{SII}]\lambda\lambda 6716, 6731$ ELRs in the spectrum of LkH α 321 are shown in Figure 4.7. Spectro-astrometric plots of these lines are presented in Figure 4.8. The $[\text{SII}]\lambda 6731$ line peaks at a velocity of -340 km s^{-1} . I estimate the peak LSR velocity of the $[\text{OI}]\lambda 6300$ line to be at $-412 (\pm 5) \text{ km s}^{-1}$. the $\text{H}\alpha$ line profile is clearly a P-Cygni profile. A blue-shifted absorption feature is present at $\sim 350 \text{ km s}^{-1}$. Also at this velocity a $\text{H}\alpha$ knot at $7''$ is detected. No offset in the $\text{H}\alpha$ ELR at the source is detected and the difference between the strength of the continuum emission and $\text{H}\alpha$ line-wings is reflected in the increased scatter in the $\text{H}\alpha$ blue-wing. The $\text{H}\alpha$ red-wing is also noisy but is generally offset in a positive direction. This is due to some weak $[\text{NII}]\lambda 6583$ emission close to the source and a $[\text{NII}]\lambda 6583$ knot also at $\sim 7''$.

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LkH α 321

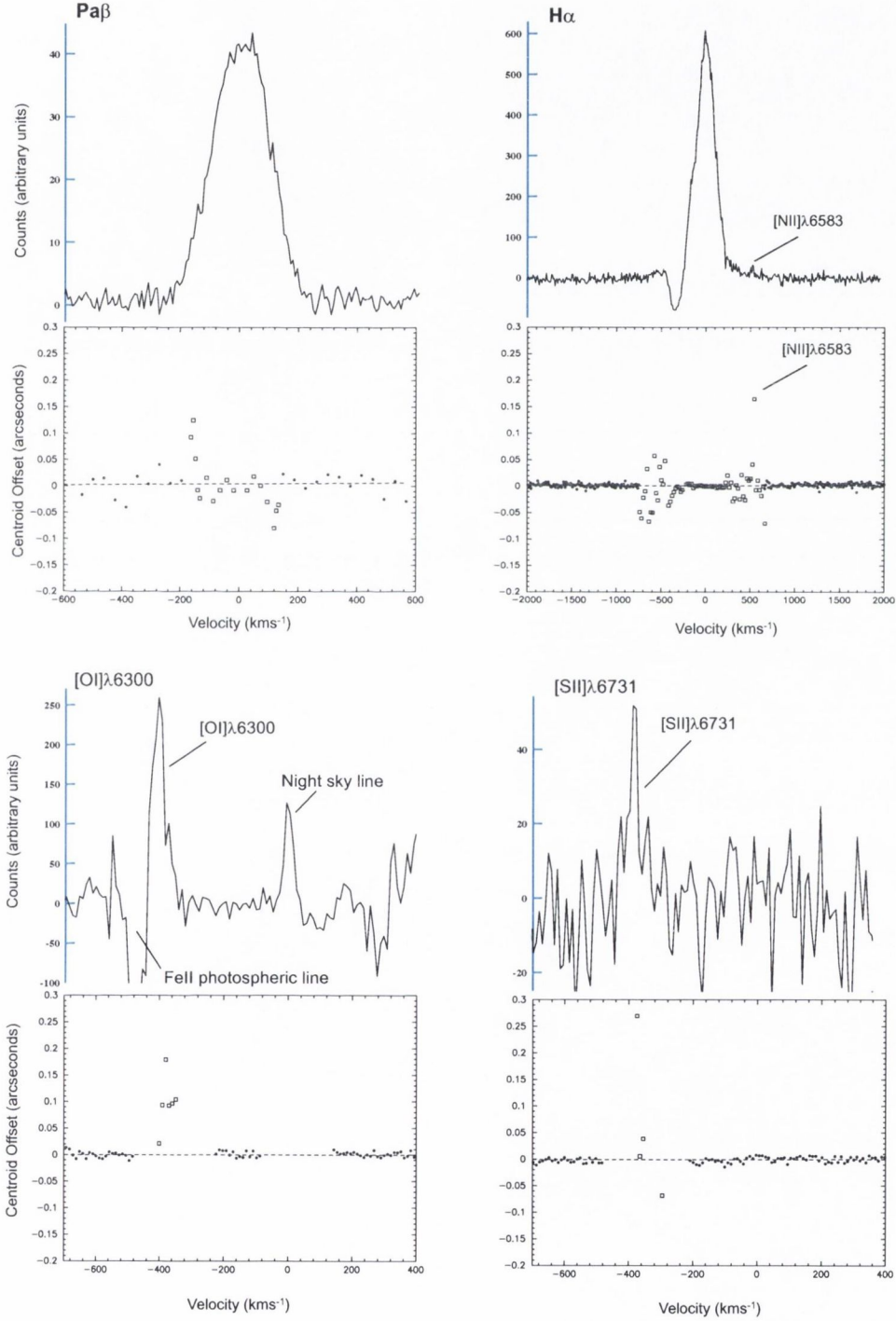


Figure 4.8: Emission line profiles and corresponding spectro-astrometric plots of the $\text{Pa}\beta$, $\text{H}\alpha$, $[\text{OII}]\lambda 6300$ and $[\text{SII}]\lambda 6731$ ELRs in the spectrum of LkH α 321. The P.A. is 208° in the positive offset direction. All velocities are LSR velocities. Note the presence of some weak $[\text{NII}]\lambda 6583$ emission next to the $\text{H}\alpha$ line.

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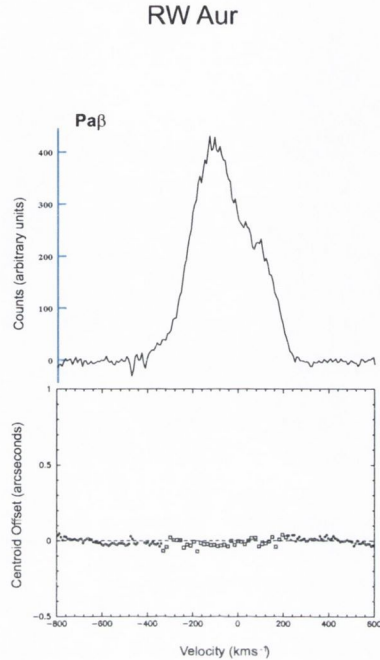


Figure 4.9: Emission line profile and corresponding spectro-astrometric plot of the $\text{Pa}\beta$ ELR in the spectrum of RW Aur. The P.A. is 125° in the positive offset direction. All velocities are LSR velocities and the systemic velocity of the source is quoted in the results section.

4.2.4 RW Aur (HH 229)

RW Aur is located in the Taurus-Auriga system at a distance $d \sim 140$ pc. It is a complex multiple star system with the primary or brightest stellar component A having a separation of about $1''.4$ from the close binary B & C (separation $0''.12$) (Ghez, Neugebauer, & Matthews, 1993). Ghez, Neugebauer, & Matthews (1993) made their observations in the K-band and components were assigned the letters A, B, C based on the relative K-band flux of the stars at the time, with A being the brightest. Component A may itself be a spectroscopic binary (Gahm et al., 1999). The HH 229 jet is a bipolar outflow associated with component A. It was first discovered by Hirth, Mundt, & Solf (1994b) by long-slit spectroscopy in $\text{H}\alpha$ and several forbidden emission lines. Their results showed that the southeastern blue-shifted jet extended over $22''$. Later studies by Eisloffel & Mundt (1998) however suggest a total length of at least $145''$ for the bipolar outflow. Results presented McGroarty & Ray (2004b) put this length at approximately $7'$. Coffey et al. (2004) also study the possible rotation in the jet from RW Aur.

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RW Aur formed part of the original $[\text{FeII}]$ study outlined in Chapter 3. See Figures 4.3 and 4.4. In the red-shifted lobe the radial LSR velocity peaking at $150 (\pm 10) \text{ kms}^{-1}$ extends to almost $0''.8$. The systemic velocity for this source is approximately $+6 \text{ kms}^{-1}$ (Ungerechts & Thaddeus, 1987). In the blue-shifted lobe the LSR radial velocity peaks at approximately $-175 (\pm 10) \text{ kms}^{-1}$ and reaches an offset of $\sim 1''.2$. $\text{Pa}\beta$ emission is also seen from RW Aur. The line profile is shown in Figure 4.9. Folha & Emerson (2001) classified this line profile as Inverse P Cygni (see section 4.3.2) and RW Aur is, in fact, long known to show IPC profiles (Mundt & Giampapa, 1982). However the red-shifted absorption feature is very weak in $\text{Pa}\beta$. It has a FWHM of $\sim 320 \text{ kms}^{-1}$ and its blue-wing extends to $\sim -400 \text{ kms}^{-1}$. No offsets are measured in the $\text{Pa}\beta$ ELR.

4.3 Discussion

4.3.1 Explaining HI Emission Lines

Considerable effort has been made over the last 20 to 30 years to try to model atomic hydrogen emission lines from T-Tauri stars. To date the principal models have involved magnetically driven winds and more recently, magnetospheric accretion. A good understanding of how these HI emission lines form is important as it enables us to use them as diagnostic tools.

The Balmer series of lines and in particular the $\text{H}\alpha$ line have been the basis of the majority of studies to date. The major advantage of the $\text{H}\alpha$ line for high resolution work is that it is generally the brightest spectroscopic feature seen in optically visible YSOs and the most common. Its wavelength falls near the peak sensitivity of a CCD hence one can observe it even when it is relatively faint in absolute terms. Historically it was easier from a technical point of view to observe emission lines in the optical, as techniques for observing emission in the NIR, for example, were not well developed.

Reipurth et al. (1996) presented an extensive study of $\text{H}\alpha$ emission from YSOs. They categorised the profiles into four different types (illustrated in Figure 4.10) in an aim to propose a scheme that reflected the underlying physical processes responsible for the line, yet was also able to deal with a greater variety of profiles. Type I profiles are normally symmetric, slightly blue-shifted (they can however be occasionally red-shifted) and show no absorption features. Type II are double

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peaked with the intensity of the second peak exceeding half the strength of the main peak. Type III profiles are also double peaked but the intensity of the second peak is less than half the intensity of the main peak. Types II are III assigned the letters R or B depending on whether the secondary peak is blue or red-shifted with respect to the primary peak. Lastly Type IV profiles are similar to Type I but they show an absorption feature which marks the edge of the emission. In other words depending on whether this absorption feature is blue or red-shifted the Type IV profile corresponds to either a P Cygni (PC) or Inverse P Cygni (IPC) profile and is appended with either the letter B or R. Their results showed that 25% of T-Tauri stars had a Type I profile and 33% had a Type IIIB profile. They found that very few CTTSs in their sample had a PC or IPC $\text{H}\alpha$ line profile.

Reipurth et al. (1996) also discussed in depth the different models used over the years to explain HI (Balmer) emission lines. I will now briefly summarise some of these models in order to give an idea of the debate on the formation of HI lines. Historically IPC and PC profiles were explained through accretion and wind models respectively. However the features of these lines, that models have struggled to explain are their large Full Width Half Maxima (FWHM), their symmetry and the presence of extensive emission wings. Type I profiles incorporate all these features.

The majority of mass loss models assume the wind is magnetically driven. Thermally driven winds were discounted as they could not reproduce the broad line-widths seen. Early models suggested Alfvén waves propagating outwards as the wind driving mechanism (Lago, 1979; Decampli, 1981). These models did not attempt to fit the $\text{H}\alpha$ line as it is optically thick, thus an adequate treatment of radiative transfer had to be included. Higher Balmer lines that were assumed to be optically thin were used instead.

Improvements in the treatment of radiative transfer were made by Natta, Giovanardi, & Palla (1988) and Hartmann & Kenyon (1990). Hartmann & Kenyon (1990) used a spherical wind model where again the driving mechanism was Alfvén waves. Overall, models did not match the observations well as the computed $\text{H}\alpha$ and $\text{H}\beta$ profiles were broader and less symmetric than observed, with blue-shifted absorption features that were also broader and deeper than seen.

Calvet, Hartmann, & Hewett (1992) described a wind that originated in a boundary layer between a star which is rotating slowly and a disk which is rapidly rotating and flowed occupying a cone-like geometry. Models produced central and blue-shifted absorption but the level of absorption exceeded that observed. Also,

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centrally peaked Type I profiles could not be reproduced, even when a rotational velocity component was adopted.

Calvet & Hartmann (1992) suggested a different approach based on the MAM, see also Königl (1991) and Shu et al. (1994). They suggested that accretion is restricted to an axially symmetric configuration by the dipolar stellar magnetic field. This magnetic field truncates the disk at a certain radius and hence there are magnetic field lines connecting the star to the disk. Accretion onto the star occurs along these magnetic field lines. These models were improved upon by Hartmann, Hewett, & Calvet (1994) and Muzerolle, Calvet, & Hartmann (1998a). Muzerolle et al (1998) improved further on the work by considering a multi-level atom in equilibrium rather than the 2-level model used by the earlier authors. It was also noted that the size of the inner and outer radii of the magnetosphere, the temperature and the inclination angle all influence the profile of the Balmer lines. A good overall agreement was found between observations and computed profiles especially in the case of IPC profiles. The major discrepancy lay in the fact that they could not reproduce the line-wings. They suggested that the high velocity wings were not actually due to the higher velocity infalling material but due to Stark broadening. This hypothesis was tested but it was found that the contribution was small. They also suggested that the emission that makes up the line-wings may result from dynamic zones other than zones of infall i.e. zones of outflow.

In summary, infall models have produced the most promising results but discrepancies such as large FWHMs and the presence of line-wings still persist. Even though IPC profiles can be naturally explained by infall models Type I profiles cannot be accounted for. Recently work has been extended to other line series for example the Brackett series (Najita, Carr, & Tokunaga, 1996) and more importantly in the context of this thesis the Paschen series (Folha & Emerson, 2001) which I shall discuss next.

4.3.2 Folha and Emerson Study

Folha and Emerson (2001) carried out the first extensive study of $\text{Pa}\beta$ and $\text{Br}\gamma$ near-infrared hydrogen emission lines from T-Tauri stars. I will concentrate on their findings for the $\text{Pa}\beta$ line. They firstly sorted the emission line profiles according to the classification scheme proposed by Reipurth et al. (1996), described above.

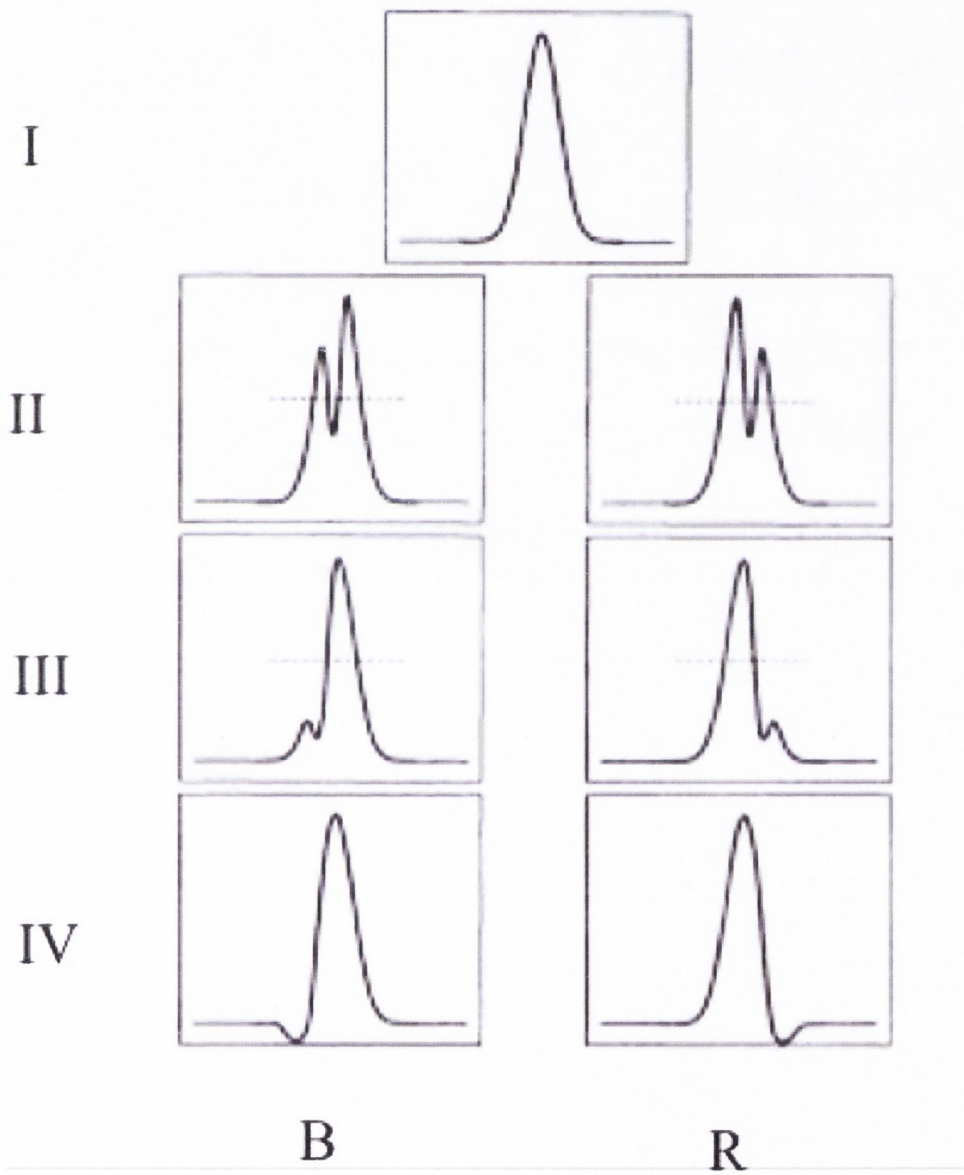


Figure 4.10: Diagrammatic of the Reipurth et al. (1996) scheme for classifying $\text{H}\alpha$ line profiles. Type I profiles are symmetric with extensive line-wings. Type II profiles are double peaked with the intensity of the secondary peak $>$ half the intensity of the primary peak. Type III profiles are also double peaked but the intensity of the secondary peak is $<$ half the intensity of the primary. Lastly Type IV profiles have an absorption component and are either P-Cygni or Inverse P-Cygni in nature depending on whether the absorption dip is blue or red-shifted.

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$\text{Pa}\beta$ emission from 49 CTTSs was studied. Of the 49 stars the authors concluded that 53% of the $\text{Pa}\beta$ line profiles were Type I and 34% were Type IVR (IPC) profiles. In summary Type I profiles were broad with a FWHM between 100 and 300 kms^{-1} . They were slightly blue-shifted and nearly symmetric. The average maximum velocities observed were -282 kms^{-1} and -240 kms^{-1} respectively for the red and blue-wings. When they compared these results to predictions made by the models, they concluded that the infall models produced lines that were too narrow and wings that extended to velocities that were too small. IPC profiles on the other hand must arise largely from infalling material, for two reasons. Firstly the red-shifted absorption feature must be formed in infalling material as it is located at velocities of the order of the free-fall velocity at a few stellar radii. The second reason stems from a trend described by the authors, associating the amount of emission seen in IPC profiles with accretion rates.

So it is clear then that, as with the Balmer series, the major discrepancy between computed profiles and observations in the case of the $\text{Pa}\beta$ line, lies in failure of studies based on the MAM to predict Type I profiles. In an attempt to account for this the authors considered several ideas. Firstly, the systems geometry may play a role in determining the shape of the line profiles. The MAM predicts red-shifted absorption for systems observed at high inclinations. The authors looked at the distribution of inclinations for a sample of the stars whose inclinations were known. They noted no significant difference between the distribution of Type I and IPC sources. However this result was obtained from a small sample of stars and should be considered with extreme caution. Secondly, they suggested that it may be possible that the presence of a red-shifted absorption feature is related to the temperature of the accretion shock. This temperature is not, however, known accurately enough in order to be able to investigate this idea. Lastly, according to Muzerolle, Calvet, & Hartmann (1998a) if HI emission originates in infalling gas then the magnetospheric accretion model predicts a correlation between emission line strength and accretion rate. Folha & Emerson (2001) find no such agreement for Type I profiles, but there does seem to be a trend for IPC profiles. Stars with larger accretion rates tend to have a larger EW in the emission component of the IPC $\text{Pa}\beta$ line profile.

Looking at this new set of $\text{Pa}\beta$ data in the same manner as Folha & Emerson (2001) it is clear that both sets of results agree well. DG Tau, V536 Aql and LkH α 321 all have Type I $\text{Pa}\beta$ profiles. DG Tau is actually slightly red-shifted with a

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radial velocity of $\sim +8 \text{ kms}^{-1}$. It has a FWHM of $\sim 225 \text{ kms}^{-1}$ and a prominent blue wing that extends to approximately -380 kms^{-1} . V536 Aql is blue-shifted to a velocity of $\sim -30 \text{ kms}^{-1}$, it has a FWHM of $\sim 167 \text{ kms}^{-1}$ and a red wing that extends to $\sim 350 \text{ kms}^{-1}$ and also a blue wing to $\sim -250 \text{ kms}^{-1}$. The $\text{LkH}\alpha$ 321 $\text{Pa}\beta$ line profile is also a Type I profile. It is perhaps the most symmetric of the three. It is blue-shifted to $\sim -2 \text{ kms}^{-1}$ and its red and blue-wings extend to approximately 300 kms^{-1} . Its FWHM is $\sim 220 \text{ kms}^{-1}$. RW Aur has a Type IV R profile. This line emission was also classified as an IPC profile by Folha & Emerson (2001) even though the red-shifted absorption feature is very weak. The RW Aur $\text{Pa}\beta$ line has a FWHM of $\sim 320 \text{ kms}^{-1}$ and its blue-wing extends to -400 kms^{-1} .

4.3.3 Spectro-astrometry

As stated an important part of this work is to produce spectro-astrometric plots of the different ELRs. In Chapter 2 a number of studies of jets on small spatial scales, where spectro-astrometry has played a vital role are reviewed. A similar approach to that adopted for those projects is used here. For each source a comparison is made between the FELs ($[\text{FeII}]$, $[\text{SII}]\lambda 6731$, $[\text{OI}]\lambda 6300$), the $\text{H}\alpha$ line and the $\text{Pa}\beta$ line. The comparison between $\text{H}\alpha$ and $\text{Pa}\beta$ is particularly interesting considering the work of Takami et al. (2001) and Takami, Bailey, & Chrysostomou (2003) (refer to Chapter 2). Table 4.2 records the peak velocities and maximum offsets measured for each CTTS in all the above lines. In the case of the FELs peak velocities can be estimated from gaussian fits to the emission line profiles and from the spectro-astrometric plots. For $\text{Pa}\beta$ and in some cases $\text{H}\alpha$, only the spectro-astrometric plots can be used to estimate the peak velocities at which the outflowing material is seen, due to the fact that the positional displacement is measured in the line-wings.

The velocities at which the $[\text{FeII}]$, $[\text{SII}]\lambda 6731$, $[\text{OI}]\lambda 6300$, $\text{H}\alpha$ and $\text{Pa}\beta$ lines are seen in the spectrum of DG Tau, V536 Aql, $\text{LkH}\alpha$ 321 and RW Aur and the measured displacements in these ELRs are outlined in section 4.2. Recall that $[\text{FeII}]$ is only strongly seen in the spectrum of DG Tau and RW Aur. Through a comparison between the spectro-astrometric plots for the FELs (and including $\text{H}\alpha$) and that for $\text{Pa}\beta$ one can conclude that $\text{Pa}\beta$ is tracing the high velocity emission from the outflows driven by DG Tau, V536 Aql and $\text{LkH}\alpha$ 321. In all these cases the displacement of the blue-wing aligns well with positional displacements measured in the FELs and $\text{H}\alpha$ i.e offsets are in the same direction and peak at velocities that

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compare well in each case. The fact that the outflow is traced by $\text{Pa}\beta$, $\text{H}\alpha$ and the FELs at very similar velocities suggests that the lines are excited in the same pocket of gas.

For V536 Aql and LkH α 321 bipolar offsets in the $\text{Pa}\beta$ ELR are recorded. In other words both the red and blue wings of the $\text{Pa}\beta$ line profile are displaced. For V536 Aql this bipolar displacement is mirrored in the $\text{H}\alpha$ line however no offsets are measured in the LkH α 321 $\text{H}\alpha$ ELR. How effectively $\text{Pa}\beta$ is tracing the red flow in both these sources cannot be confirmed by a comparison with the FELs as only blue-shifted forbidden emission is observed in all three sources. It is assumed that the red-shifted forbidden emission is obscured by the circumstellar disk and the significance of the bipolar $\text{Pa}\beta$ and $\text{H}\alpha$ offsets is discussed in section 4.3.4.

RW Aur is the final source and the only one for which there is no new optical data. However it was studied by Hirth, Mundt, & Solf (1997) so their findings are used as a reference. Results discussed in this chapter and published in Davis et al. (2003) showed [FeII] emission in both lobes at peak velocities of $\sim -175 \text{ kms}^{-1}$ and $\sim 150 \text{ kms}^{-1}$. The corresponding spectro-astrometric plot shows maximum displacements of $\sim 1''$ in both lobes. Hirth, Mundt, & Solf (1997), presented spectro-astrometric plots of the [SII] $\lambda 6731$ line and published values of peak velocity of -166 kms^{-1} and $+99 \text{ kms}^{-1}$ for the blue and red lobes respectively. In $\text{Pa}\beta$ no offsets are recorded and this is the only source in the sample showing this behaviour. This is an interesting result as the $\text{Pa}\beta$ line profile is an inverse P Cygni profile and as I discussed above, in connection with the results of Folha & Emerson (2001) and others, this type of profile is well explained by the MAM.

4.3.4 Common Trends

Circumstellar Disk Dust Holes

Results show that for three out of four of the TTSs studied, the positional displacement measured in the $\text{Pa}\beta$ line-wings is consistent with outflowing material. Central to this argument is the comparison with the optical forbidden emission from these sources. One notable feature of the FELs of T-Tauri stars is that they are generally blue-shifted. It is known that the red-shifted part of the flow is often obscured by the optically thick circumstellar disks that have been proven to exist around these stars (Edwards et al., 1993). Hence the fact that for two out of four of our sources studied here, namely V536 Aql and LkH α 321, $\text{Pa}\beta$ emission is detected from both

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Object	Emission Line	$V_B(\text{kms}^{-1})$	Offset(")	$V_R(\text{kms}^{-1})$	Offset(")
DG Tau	[FeII]	-235	6		
	[SII] λ 6731	-47; -240	0.6; 1.4		
	[OI] λ 6300	-47; -266	0.25; 1		
	$\text{Pa}\beta$	-250	0.5		
	$\text{H}\alpha$	-290	0.37		
V536 Aql	[SII] λ 6731	-20; -84	0.15; 0.9		
	[OI] λ 6300	-10; -65	0.05; 0.85		
	$\text{Pa}\beta$	-120	0.1	40	-0.085
	$\text{H}\alpha$	-270	0.065	260	-0.04
LkH α 321	[FeII]			229	
	[SII] λ 6731	-340	0.25		
	[OI] λ 6300	-412	0.17		
	$\text{Pa}\beta$	-160	0.13	120	-0.075
RW Aur	[FeII]	-175	1	150	-1
	[SII] λ 6731*	-166		99	

Table 4.2: Table comparing peak velocities and offsets measured for each source in $\text{Pa}\beta$, [SII] λ 6731, [OI] λ 6300 or [FeII]. * The [SII] λ 6731 velocity measurements for RW Aur were taken from Hirth et al (1997).

sides of the outflow, is very interesting.

As mentioned above similar spectro-astrometric results were published for the $\text{H}\alpha$ emission from RU Lupi and CS Cha by Takami et al. (2001) and Takami, Bailey, & Chrysostomou (2003). They also measured a bipolar displacement in the $\text{H}\alpha$ emission which they suggested provided further evidence in favour of the existence of dust holes in the circumstellar disks of young stars. If a gap existed it would allow the red-shifted emission to be seen. One should think of these holes/gaps as areas where dust has been cleared (and not necessarily gas), hence the opacity of the circumstellar material in this region of the disk has been lowered. It is a likely scenario that these gaps occur in more evolved T-Tauri stars where the process of planet formation has begun and the dust grains have started to grow (Testi, Natta, Shepherd, & Wilner, 2003; Shuping, Bally, Morris, & Throop, 2003; Wood, Wolff, Bjorkman, & Whitney, 2002).

To date the existence of holes/gaps in circumstellar disks has mainly been inferred from a study of the SEDs of young stars. The fact that the SEDs of many young stars show a dip at mid-infrared wavelengths, or often exhibit a small or nonexistent near-infrared excess, has been taken to prove the presence of regions of cleared circumstellar material (Jensen & Mathieu, 1997; Marsh & Mahoney, 1992;

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Mathieu, Adams, & Latham, 1991). It is very tempting to then make the inference that these regions of cleared material suggest the presence of a protoplanetary or planetary object (Steinacker & Henning, 2003; Calvet et al., 2002; Bryden et al., 2000).

In the case of RU Lupi Takami et al. (2001) measured a displacement of 20-30 mas which they claim corresponds to a projected hole radius of 3-4 AU. To further prove their point, Takami et al. (2001) plotted the SED of RU Lupi. They measured a shallow dip at 4-15 μ m which corresponds to temperatures of 200-900K and the radiative temperature at a radius of 0.1-2AU from the star. This fits well with the estimate of a hole radius of 3-4 AU taken from the extent of the displacement measured in the H α wings.

I shall now consider the possibility that the presence of a dust hole in the circumstellar disk around V536 Aql is allowing the observation of red-shifted Pa β emission. As described V536 Aql is a binary star and circumstellar material has been detected around this source. I measure a displacement in the red-wing of $\sim 0''.085$ which constrains the hole radius (as seen in Pa β) at ~ 16.5 AU at the distance of V536 Aql (200 pc). A SED for this source was available through a private communication (Gras-Velázquez et al 2005, submitted). Similar to what is reported for RU Lupi a dip in emission between 2 μ m and 16 μ m is observed, indicating a lack of material in the temperature range 180-1450 K. A value of 4.5L $_{\odot}$ is estimated by Gras Velázquez et al (2005, in preparation) for this source.

The temperature of a disk can be modelled using a simple power law radial temperature dependence

$$\mathbf{T}(\mathbf{r}) = \mathbf{T}_o(r/r_o)^{-q} \quad (4.1)$$

and Beckwith & Sargent (1993) give the exact form of this radial temperature dependence as

$$\mathbf{T}(\mathbf{r}) = (2/3\pi)^{1/4} T_*(\mathbf{r}/R_*)^{-q} \quad (4.2)$$

where T_* and R_* are the effective temperature and radius of the star and $\mathbf{r}$ is the distance corresponding to the temperature $\mathbf{T}$. Finding the exact value of q is not a trivial task. Adams et al. (1988) give the range of values of this constant as $0.5 \leq q \leq 0.75$. This is based on the assumption that the circumstellar dust is confined to a flat thin passive disk. Beckwith, Sargent, Chini, & Guesten (1990) give the variation of the temperature of a particle of circumstellar dust in radiative

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equilibrium, with distance from the star as

$$\mathbf{T}_p(\mathbf{r}) = \mathbf{T}_o(r/r_o)^{-0.4} \quad (4.3)$$

Here the particles are assumed to be distributed spherically around the star and $q=2/(4+\beta)$, where $\beta=1$ is the spectral index for the dust opacity law (Beckwith, Sargent, Chini, & Guesten, 1990; Beckwith & Sargent, 1991).

Using equation 4.2 I can estimate where in relation to the star the dust hole is located or the projected hole radius. This is done for values of q equalling 0.4, 0.5 and 0.75. Equation 4.2 simplifies to

$$\mathbf{T}(\mathbf{r}) = 0.68T_*(R_*)^q \mathbf{r}^{-q} \quad (4.4)$$

Using

$$\mathbf{L} = 4\pi\sigma T_*^4 R_*^2 \quad (4.5)$$

I obtain a value of $4.4R_\odot$ for R_* . L_* is given as $4.5L_\odot$ as stated above and as the dip in the SED is between $2\mu\text{m}$ and $16\mu\text{m}$ I choose the value of $\mathbf{T}$ at 180K, which corresponds to the temperature at the outer edge of the gap, or $16\mu\text{m}$ from $\lambda\mathbf{T} = 2.8978 \times 10^7 \text{ \AA K}$. Substituting the above values into equation 4.4 I estimate a value for the hole radius of $\mathbf{r} \approx 17 \text{ AU}$ for $q=0.4$, $\mathbf{r} \approx 5 \text{ AU}$ for $q=0.5$ and $\mathbf{r} \approx 1 \text{ AU}$ for $q=0.75$. These values confirm that the lack of excess in the SED of V536 Aql, and the transparency of the disk to the Pa β emission from the outflow, are caused by changes in the opacity of the dust in the same region of the disk.

As well as seeing red-shifted Pa β emission red-shifted H α emission from V536 Aql is also detected. Hence it is also possible to estimate the hole size from the spectro-astrometric results for the H α line. The red-shifted emission is displaced out to distance of $0''.035$ which corresponds to a radius of $\sim 7 \text{ AU}$. Overall both the SED and the spectro-astrometric data I have for V536 Aql points to the existence of a region in the disk where the opacity of the circumstellar material is low enough for red-shifted emission from both Pa β and H α to be detected. The fact that I measure a bigger gap in Pa β than in H α might be expected as the transparency of the disk should be greater at longer wavelengths. Hence it may be possible to use these lines in conjunction with other HI lines of known intensity as a diagnostic of the transparency of the circumstellar disk.

The second of the two sources for which a bipolar Pa β emission is observed is

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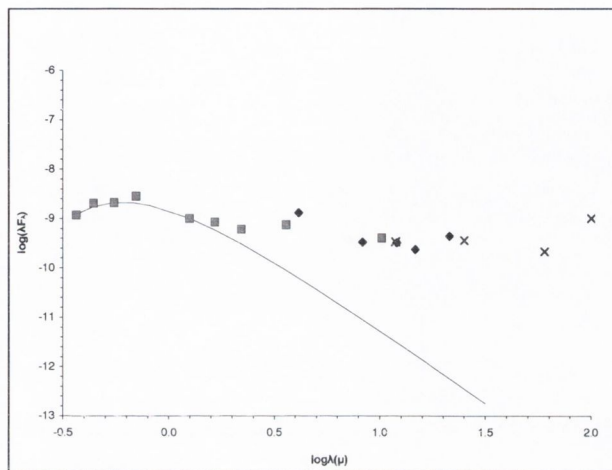


Figure 4.11: SED of LkH α 321. A blackbody curve representing the stellar photosphere is fitted to the flux at V ($0.55\mu\text{m}$). The square boxes represent data points for the U to N bands, the diamonds represent measurements taken in the bands used by the Midcourse Space Experiment (MSX) and the crosses are the IRAS points. Measurements, in the U, B, V and R bands were taken from Herbst & Shevchenko (1999), in the L and N bands from Cohen (1974), in the J, H and K bands from 2MASS.

LkH α 321. Offsets in the $\text{Pa}\beta$ red-wing out to $\sim 0''.075$ are measured. This source is at a distance of 550 pc, hence this positional displacement corresponds to a hole size of 40 AU. I plotted the SED of this source from $0.354\mu\text{m}$ (U) to $100\mu\text{m}$ and the photometric measurements in this range were obtained from a variety of sources. The flux measurements in the U, B, V and R bands were taken from Herbst & Shevchenko (1999) and in the L and N bands from Cohen (1974). The 2MASS sky survey provided the photometry in the J, H and K bands. I also accessed the Midcourse Space Experiment (MSX) archive to obtain flux measurements at $4.2\mu\text{m}$, $8.28\mu\text{m}$, $12.13\mu\text{m}$, $14.65\mu\text{m}$ and $21.34\mu\text{m}$. Lastly measurements at $12\mu\text{m}$, $25\mu\text{m}$, $60\mu\text{m}$ and $100\mu\text{m}$ were extracted from the Infrared Astronomical Satellite (IRAS) Point Source Catalogue. The clear infrared excess in the SED of LkH α 321 points to the existence of a circumstellar disk however I see no evidence for a hole in this disk.

Most infrared SEDs discussed in the literature are compiled in the above manner, using data obtained from sets of observations taken with various instruments and often spanning a long period of time. Hence the agreement of data extracted from different studies must be considered. If the source in question is unresolved in the

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aperture then contamination from nearby sources may result and the amount of contamination will vary depending on the spatial resolution of the observation. For example a beam size of $15''$ was used for observations discussed by Cohen (1974) and spatial resolutions of $18''$ and $2''$ are achieved by the MSX (Price et al., 2001) and 2MASS sky survey respectively. It is often the case that T-Tauri stars are binary companions yet it is possible in many cases to remove the contribution of the companion (Gras-Velázquez & Ray, 2005; Marsh & Mahoney, 1992). Source variability over long periods of time could also result in a lack of agreement. In the case of LkH α 321 there are no known nearby companions or sources which could cause contamination. Overall good agreement can be expected for mid-infrared points shown in the above SED and indeed the overlap between the MSX and IRAS points at $12\mu\text{m}$ confirms this. All surveys will of course be effected by contamination due to infrared cirrus (emission from interstellar dust) at $100\mu\text{m}$.

For DG Tau a displacement in only the blue-wing of the $\text{Pa}\beta$ and H α ELRS is measured. DG Tau appears less evolved than either V536 Aql or LkH α 321. This is clearly seen by the fact that it drives a very powerful outflow and has a relatively high accretion rate. See Figures 4.1 and 4.5 for a comparison between the jets from DG Tau and V536 Aql. Also DG Tau is known to have a flat SED (Adams, Shu, & Lada, 1987; Lodato & Bertin, 2001). Hence the SED of DG Tau shows no evidence of a disk gap or hole which would allow the red-shifted jet to be traced in $\text{Pa}\beta$. This ties in well with results for V536 Aql. If the lower opacity which allows us to see the red-shifted $\text{Pa}\beta$ emission is a result of the growth in the dust grains in the inner regions of the circumstellar disk or clearing of dust due to the presence of a planet, then it would be reasonable to expect the circumstellar disk of a less evolved YSO like DG Tau to have no such regions of low opacity.

In the above calculations of the dust hole size from the spectro-astrometric offsets, the inclination of the jet with respect to the line of sight (I) was ignored. In the extreme case of a edge-on disk i.e. $I = 90^\circ$, the jet is virtually in the plane of the sky and the gap is invisible. For a near face on disk, $I = 0^\circ$ and the observed offset of the red-shifted jet, is a maximum. The relationship between the projected measured size of the gap, S_{hole}^* from the spectro-astrometric observations and S_{hole} can be given as

$$S_{hole} = \frac{S_{hole}^*}{\cos I} \quad (4.6)$$

See also Figure 4.12

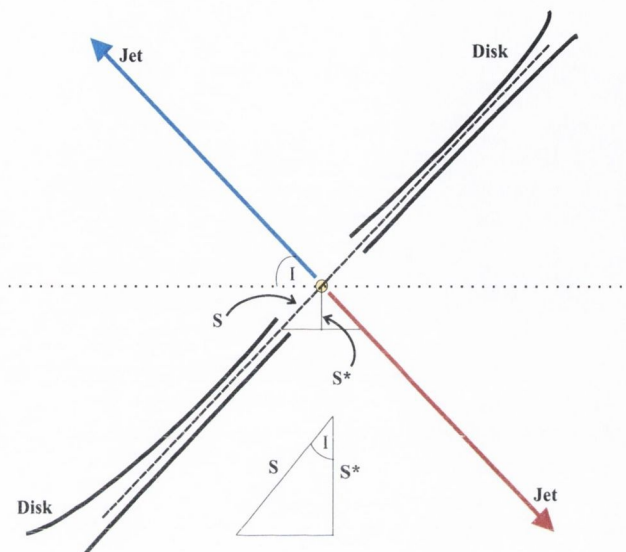


Figure 4.12: The inclination angle of the jet/disk with respect to the line of sight also effects our calculation of the dust hole size. The jet is inclined at an angle I and the measured hole size from the spectro-astrometric observations S^* equals $S \cos I$ where S is the actual gap size.

For both V536 Aql and LkH α 321 discussed above, I , is not known but can perhaps be estimated. The average value of the high velocity emission from V536 Aql (seen in [OI] λ 6300 and [SII] λ 6731) is $\sim 80 \text{ kms}^{-1}$. The velocity of a typical HVC is $\sim 100 \text{ kms}^{-1}$ hence a reasonable estimate of I for V536 Aql is $\approx 45^\circ$, which increases the value of S_{hole} given above to $\approx 23 \text{ AU}$. The high velocities and small offsets (for the blue-shifted jet) measured from LkH α 321 point to an inclination of the jet which is close to being perpendicular to the plane of the sky. Hence I is $\approx 0^\circ$ and S_{hole}^* is approximately S_{hole} .

The Diagnostic Zones of Different Lines

Previous spectro-astrometric studies (Hirth, Mundt, & Solf, 1997) have shown that amongst the individual optical FELs spatial offset increases with decreasing density. For example the displacement at high velocities has been shown to be larger in [SII] than in [OI] and this suggests decreasing densities with increasing distance from the star (Hamann, 1994). Results presented in this chapter now extend this argument from the optical into the near-infrared.

Clearly the different lines trace conditions at different average distances from

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the central star and the average distance increases from $\text{Pa}\beta$ to the optical FELs and then to [FeII]. For example, for DG Tau the outflow is mapped in [FeII] out to $6''$, in [SII] $\lambda 6731$ out to $1''.4$, in [OI] $\lambda 6300$ out to $1''$ and finally in $\text{Pa}\beta$ out to $0''.5$. In V536 Aql displacement decreases for the emission lines in the same order as above, from $0''.9$ to $0''.85$ to $0''.1$. Lastly for LkH α 321 offsets decrease from $0''.25$ to $0''.17$ to $0''.13$.

Hamann (1994) gives the temperatures and densities of the [OI] and [SII] emission regions as $9,000 \leq T_e \leq 14,000\text{K}$, $n_e \leq 5 \times 10^5$ to $\sim 10^7 \text{ cm}^{-3}$ and $T_e \geq 13,000\text{K}$, $10^3 \leq n_e \leq 7 \times 10^4 \text{ cm}^{-3}$ respectively. For atomic hydrogen lines like $\text{Pa}\beta$ it is believed that they are primarily formed under similar temperatures as the optical FELs but at typically much higher densities. Kwan & Alonso-Costa (1988) estimate the density of the hydrogen line emission zone at 10^{10} to $\sim 10^{12} \text{ cm}^{-3}$. Muzerolle, Hartmann, & Calvet (1998b) modelled Na D and hydrogen lines to constrain the physical parameters of the magnetospheric infall zone and they estimated gas temperatures in this region of about $10,000\text{K}$ (in the case of DP Tau). It is also clear from the spectro-astrometric results that $\text{Pa}\beta$ is formed very close to the star. Lastly [FeII] emission derives from gas at a density of $n_e \sim 10^4 \text{ cm}^{-3}$ and a temperature of the order of 10^4K (Hollenbach & McKee, 1989).

This comparison of the displacement in the different emission lines clearly reflects the fact that density decreases as we move away from the driving source of the outflows. $\text{Pa}\beta$ forms in the regions very close to the star where temperatures and densities are high and where one is observing both accretion and outflow. In fact results suggest that the bulk of the $\text{Pa}\beta$ emission forms in the hot accretion zones as I find that only the emission making up the wings shows spatial offsets. The optical FELs form further out where temperatures are similar but densities are lower. Lastly the [FeII] traces the outflow out to distances where densities are much lower again.

Conclusion

To summarise, results of a study where the $\text{Pa}\beta$ emission from four CTTs is examined using spectro-astrometry for evidence of the presence of outflows, were presented. The key to this work is a direct comparison between the $\text{Pa}\beta$ and FELRs spectra. FELs are strong tracers of outflows. The overall conclusion of this work

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is that $\text{Pa}\beta$ can trace outflow activity in CTTs and this statement is strongly supported by the following points.

1. The HI $\text{Pa}\beta$ line profiles of three out of four of the sources are all Type I profiles in accordance with the classification scheme of Reipurth et al. (1996). The MAM which is the basis for theories describing how atomic hydrogen emission lines form in accretion zones connected with YSOs, cannot account for Type I profiles. In particular it cannot explain the presence of the symmetric line-wings.
2. Positional displacements in the $\text{Pa}\beta$ line-wings were measured in all three sources with Type I profiles. This displacement of the $\text{Pa}\beta$ ELRs matches what is seen in the FELs for all the sources. The velocities at which the $\text{Pa}\beta$ offsets are measured are comparable to those at which the outflows are seen in the FELs and the sense of the outflows (i.e. blue or red-shifted) reflected in the $\text{Pa}\beta$ plots matches spatially that which is seen in the optical FELs.
3. For DG Tau and V536 Aql an outflow component to the $\text{H}\alpha$ line is also detected and in both cases the $\text{H}\alpha$ and $\text{Pa}\beta$ results agree. Only a blue-shifted component is seen in $\text{H}\alpha$ and $\text{Pa}\beta$ for DG Tau and both the red and blue-shifted flows are seen in $\text{Pa}\beta$ and $\text{H}\alpha$ for V536 Aql.
4. The fourth source, RW Aur has an Inverse P Cygni profile which is best explained by the MAM. I measure no positional displacements in the $\text{Pa}\beta$ emission from RW Aur which is consistent with this explanation.

A second important result of this study is that it may be possible to use spectro-astrometric observations of the $\text{Pa}\beta$ ELRs of CTTs to study the transparency of the circumstellar disks of CTTs. I suggest that the bipolar nature of the $\text{Pa}\beta$ and $\text{H}\alpha$ emission from V536 Aql may be indicative of the presence of a hole or region of low opacity in the circumstellar disk of this source. This suggestion is supported by the SED of V536 Aql. Interestingly the comparison between the $\text{H}\alpha$ and $\text{Pa}\beta$ lines shows that through studying the displacement of several HI lines of known intensity a transparency profile of the disk might be constructed. This idea is further discussed in Chapter 7.

It is fair to say that the argument in favour of the $\text{Pa}\beta$ line-wings being formed in areas of outflow activity is strong. An extensive study of TTSs and Class I sources

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is needed to add further weight to this argument. As the Class I sources are known to drive more powerful outflows than the T-Tauri stars it will be interesting to see if this is reflected in $\text{Pa}\beta$ emission. Other studies such as that by Takami et al. (2001) mentioned above, back up these conclusions.

Chapter 5

Using Spectro-astrometry to Map Outflow Activity from Herbig Ae/Be stars

Introduction

In Chapters 3 and 4 outflow activity in a sample of Class I sources and CTTs was explored, through a study of the spatio-kinematic properties of their optical and near-infrared line regions. The aim was to probe the outflows as close to their driving sources as possible. Using spectro-astrometry (as outlined in Chapter 2) information on scales less than the seeing of the observations was successfully recovered. Through my work (Davis et al., 2003; Whelan et al., 2004) and indeed previous studies by numerous other authors our comprehension of how outflows behave close to where they are launched has been much improved. This is especially true for the CTTs (Hirth, Mundt, & Solf, 1994b, 1997). However in comparison to the much focused on CTTs, relatively little is known about the jet launch regions of their higher mass equivalents the Herbig Ae/Be stars (Herbig, 1960). To date the emphasis has been on comparing the properties of the Herbig Ae/Be stars to those of the CTTs. Like the CTTs, Herbig Ae/Be stars power strong bipolar outflows (Mundt & Ray, 1994; McGroarty et al., 2004a) and their emission line spectra in the optical and near-infrared show many similarities to T-Tauri spectra (Finkenzeller & Mundt, 1984; Finkenzeller, 1985; Hamann & Persson, 1992; Hamann, 1994; Nisini, Milillo, Saraceno, & Vitali, 1995). Results presented by Hillenbrand, Strom, Vrba, & Keene

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(1992) on accretion activity in intermediate mass sources show that their accretion disks are scaled up versions of low mass disks. They conclude that accretion rates are ~ 100 times and disk masses are typically 10 times, those for TTSSs.

Böhm & Catala (1994b) were one of the first groups to explore the FELRs of a large sample of Herbig Ae/Be stars and to investigate whether models which explain the FELRs of CTTSs i.e. the *disk-wind* model of Kwan (1997), can also explain the forbidden line profiles of these higher mass YSOs. Altogether they studied 33 stars, 17 of which had [OI] λ 6300 emission. However only one of their sources, R Mon showed an [OI] λ 6300 emission line profile similar to the FEL profiles of the CTTSs, in that it was asymmetric and blue-shifted. Overall the FEL profiles of the sources included in the study were found to be symmetric and centred at zero. Böhm & Hirth (1997) argue that this symmetry rules out the disk-wind model for the majority of Herbig Ae/Be stars and may even question the existence of circumstellar disks in these cases. Corcoran & Ray (1997) present a second comprehensive study, of 56 Herbig Ae/Be stars which reveals that of the 28 sources showing [OI] λ 6300 emission 20 sources have blue-shifted forbidden emission and for four out of 20 of these sources the emission is blue-shifted and double peaked. Overall, the results of these two studies reveal that blue-shifted, multi-component FEL profiles are far less common for the Herbig Ae/Be stars than for the CTTSs. However for the Herbig Ae/Be stars whose FELRs do exhibit the above features it is a strong possibility that the outflows from these sources are launched in the same manner as T Tauri jets.

Further evidence that outflows from Herbig Ae/Be stars are launched in a similar manner to T Tauri flows comes from comparisons of their near-infrared colours with the relative strengths of their FELs (Corcoran & Ray, 1998b). For example the correlation between the equivalent width of the [OI] λ 6300 line and the near-infrared colours seen in TTSSs, is repeated in the Herbig Ae/Be stars. Corcoran & Ray (1998b) also found that the [OI] λ 6300 line luminosity correlates better with excess infrared luminosity than with stellar luminosities, supporting the idea that Herbig Ae/Be winds are accretion driven. If the Herbig Ae/Be stars and TTSSs stars with forbidden emission are grouped together, the correlation between mass loss rate (as indicated by the strength of the forbidden-line emission) and infrared excess spans nearly 5 orders of magnitude in luminosity and a range of masses from $\sim 0.5 M_{\odot}$ to $\sim 10 M_{\odot}$ (Corcoran & Ray, 1998b).

In this Chapter I examine using spectro-astrometry, the optical FEL spectra

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of four Herbig Ae/Be stars. I shall attempt to clarify further our understanding of how well activity in the jet launch region of the Herbig Ae/Be stars compares to what is accepted for the CTTSs. All these sources were shown by Corcoran & Ray (1997) to have FEL profiles reminiscent of the CTTSs. Overall I find that the spatial properties of the forbidden emission and $H\alpha$ line regions exhibit the same features as revealed using spectro-astrometry for the CTTSs and indeed the Class I sources discussed in Chapter 3. In particular the separate origins of the low and high velocity FEL components are highlighted, confirming the validity of extending the CTTS jet/wind launching model to these Herbig Ae/Be stars. Interesting characteristics of individual sources are also uncovered. For example two of the stars, namely PV Cep and LkH α 233, show evidence of *dust holes* in their circumstellar disks, similar to what I report for V536 Aql and LkH α 321 in Chapter 4. Many Herbig Ae/Be stars are deeply embedded and are often the exciting sources of reflection nebulae (R Mon and V645 Cyg). R Mon and V645 Cyg are not seen directly but entirely in scattered light and this is reflected in the spectro-astrometry.

5.1 Observations

Observations presented in this chapter originally formed part of the following studies, (Corcoran, 1995; Corcoran & Ray, 1997, 1998a,b). The above authors carried out one of the first major, intermediate resolution spectroscopic surveys of the extended FELRs of the Herbig Ae/Be stars. Their aim was to compare these regions to the FELRs of the CTTSs. Observations of the sources presented in this paper were taken in La Palma on the INT with the IDS. The data was acquired from the INT data archive.

There were two observing runs, one in July 1993 and a second in December 1994. The July 1993 data was taken using the R632V grating and the EEV5 CCD, giving a spectral resolution of $0.39\text{\AA}$ per pixel. The December 1994 run used the R1200Y grating and the TEK3 CCD. The resulting spectral resolution was $0.70\text{\AA}$ per pixel. The pixel scale was $0''.33$ per pixel. Table B.1, in Appendix B gives the value of the seeing for each of the observations. Table 5.1 lists the sources, their P.A.s, when they were observed and the velocity resolution at $H\alpha$ line. The spectra were bias subtracted, flat fielded and wavelength calibrated using standard IRAF

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Source	RA (J2000)	Dec (J2000)	P.A.	Obs. date	Velocity resolution at H α (2 pixels)
R Mon	06 39 10.1	+08 44 27	0°	Dec '94	36 kms ⁻¹
PV Cep	20 45 54.29	+67 57 38.8	25°	Jul '93	65 kms ⁻¹
V645 Cyg	21 39 58.0	+50 14 24	24°	Jul '93	65 kms ⁻¹
			80°	Dec '94	36 kms ⁻¹
			325°	Dec '94	36 kms ⁻¹
LkH α 233	22 34 40.9	+40 40 05	30°	Dec '94	36 kms ⁻¹
			60°	Dec '94	36 kms ⁻¹
			70°	Dec '94	36 kms ⁻¹
			150°	Dec '94	36 kms ⁻¹

Table 5.1: The above table lists the Right Ascension and Declination, Position Angle (P.A.), observation date and velocity resolution for each source. Both V645 Cyg and LkH α 233 were observed at several P.A.s.

routines. The wavelength calibration was done using Copper-Neon and Copper-Argon spectra. The absolute velocity calibration for all sources was checked by self-calibrating the arc. Variations were less towards the centre of the array, however on average they were found to be ~ 3 kms⁻¹.

5.2 Results

As stated the aim of this study is to gain a deeper understanding of the optical forbidden and H α ELRs of Herbig Ae/Be stars using spectro-astrometry. For each source I firstly present the position-velocity diagrams to highlight the interesting features in the spectra and then secondly the emission line profiles and spectro-astrometric plots. The error in the position of the continuum emission is relatively constant across the whole continuum and is measured at an average value of 14 mas. The average errors for the H α and forbidden ELRs are 20 and 30 mas respectively.

5.2.1 R Mon (HH 39)

R Mon the illuminating source of the bipolar nebula NGC 2261 (the Fan nebula), is the driver of a large bipolar outflow which includes the blue-shifted HH 39 complex, some 7' to the north. It is located at a distance of ~ 800 pc and is one of the brightest Herbig Ae/Be stars known with a luminosity of $L \sim 740L_{\odot}$ (Mundt, Brugel, & Bührke, 1987). The Fan nebula is a much studied example of a reflection nebula.

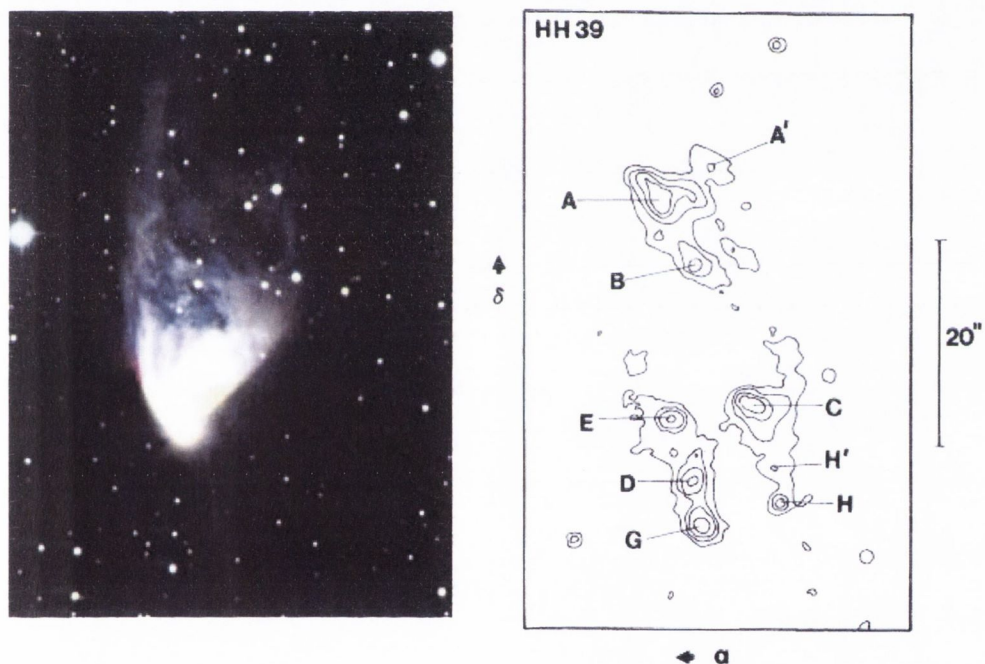


Figure 5.1: Image of the Fan nebula or the northern lobe of NGC 2261 taken by David Malin on the AAT (left) plus the HH 39 complex of knots (right). The image of the Fan nebula is $\sim 3.7'$ wide. The contour map of HH 39 is derived from a R band CCD frame taken at the prime focus of the AAT. The designation of the individual knots is indicated. This contour map is taken from Walsh & Malin (1985).

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Indeed it is also often referred to as “Hubbles Variable Nebula” as Hubble (1916) was the first to note that its appearance could change over a period of months. The nebula consists of bipolar dusty hollow shells, evacuated by the powerful bipolar outflow and the light from R Mon is scattered and reflected off the dusty walls of the nebula causing the nebula to light up. The southern lobe which corresponds to the counter-flow, is obscured by the optically thick disk surrounding R Mon (Aspin et al., 1985b; Close et al., 1997). Close et al. (1997) image both the northern and southern lobes in the J and K bands. The dust between the northern and southern parts of the nebula is dense enough that the southern part is still completely obscured in the R-band. Figure 5.1 is an optical image of the Northern lobe taken with the Anglo Australian Telescope (AAT).

Early studies detected the presence of a bipolar molecular outflow (Canto, Rodríguez, Barral, & Carral, 1981) and Brugel, Mundt, & Bührke (1984) first observed both the highly collimated jet and counter-jet. Böhm & Catala (1994b) studied the optical FE from this source. Of the 33 Herbig Ae/Be stars in their sample R Mon was the only source with asymmetric, blue-shifted [OI] λ 6300 lines. This was strong evidence in favour of the presence of a circumstellar disk around R Mon. Indeed the existence of a circumstellar disk had already been inferred from linear polarisation maps (Bastien & Ménard, 1990). The results presented by Böhm & Catala (1994b) were confirmed by Corcoran & Ray (1997). As part of this study R Mon was observed in both the [SII] $\lambda\lambda$ 6716,6731 and [OI] $\lambda\lambda$ 6300,6363 doublets and I report on the spatial properties of these lines below.

Close to the source at a PA of 0° only low velocity forbidden emission peaking at -45 kms^{-1} ($\pm 7 \text{ kms}^{-1}$) in [OI] λ 6300, -60 kms^{-1} ($\pm 7 \text{ kms}^{-1}$) in [NII] λ 6583 and -30 kms^{-1} ($\pm 7 \text{ kms}^{-1}$) in [SII] λ 6731, is detected. Velocities of up to 130 kms^{-1} are reached in [OI] λ 6300 and [SII] λ 6731 at distances of approximately $4''$ from the source. Very strong $\text{H}\alpha$ emission is also observed. The $\text{H}\alpha$ profile is double peaked with the primary peak at $\sim +95 \text{ kms}^{-1}$ and the secondary peak at $\sim -160 \text{ kms}^{-1}$. The high red-shifted velocity of the primary peak is curious as normally the primary peak is at $\sim 0 \text{ kms}^{-1}$ and the secondary is blue-shifted and representative of the blue-shifted outflow. This is suggestive of a contribution to the $\text{H}\alpha$ line from the counter-flow and this result is confirmed by Walsh & Malin (1985). The velocities and offsets measured for each ELR are recorded in Table 5.2. The position velocity diagrams of the ELRs, including the $\text{H}\alpha$ ELR are presented in Figure 5.2 and the emission line profiles and corresponding spectro-astrometric plots in Figure 5.5. The

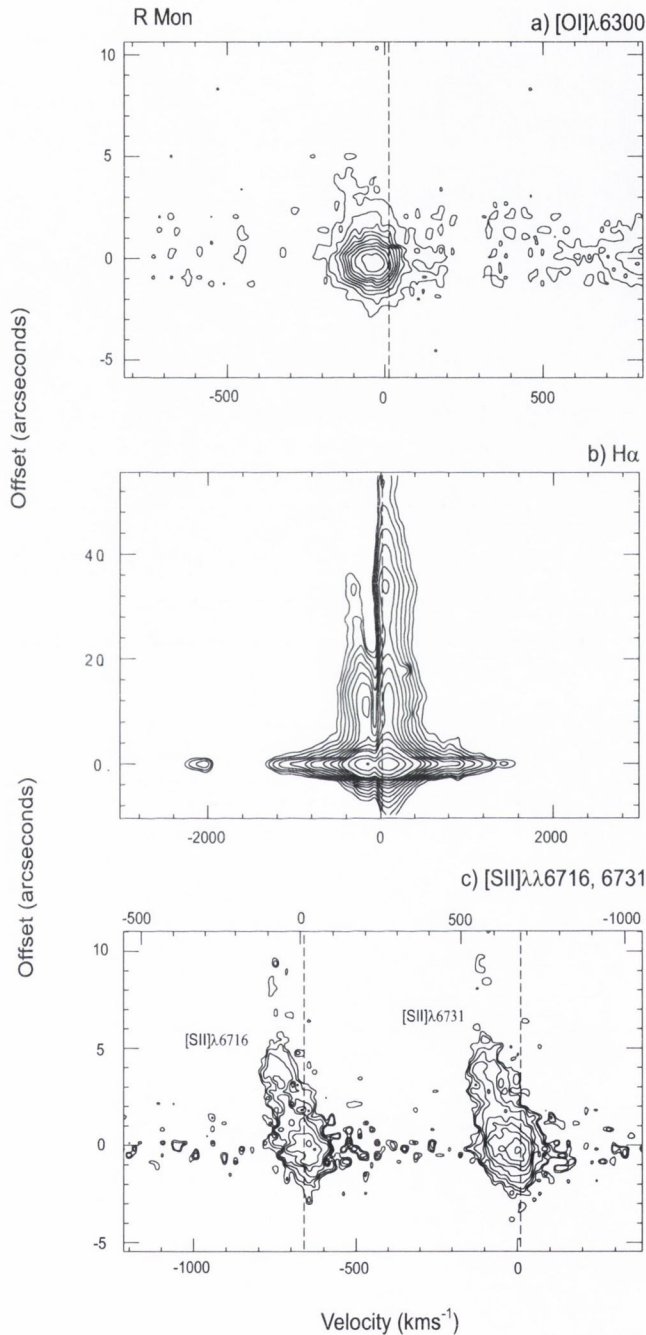


Figure 5.2: Position velocity diagrams of the [OI]λ6300, Hα and [SII]λλ6716,6731 ELRs at R Mon. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. All velocities are LSR velocities. For the [SII]λλ6716,6731 ELRs the velocity scale for the [SII]λ6731 line is marked along the bottom of the position velocity diagram and the scale for the [SII]λ6716 is marked along the top. The dashed line indicates the systemic velocity.

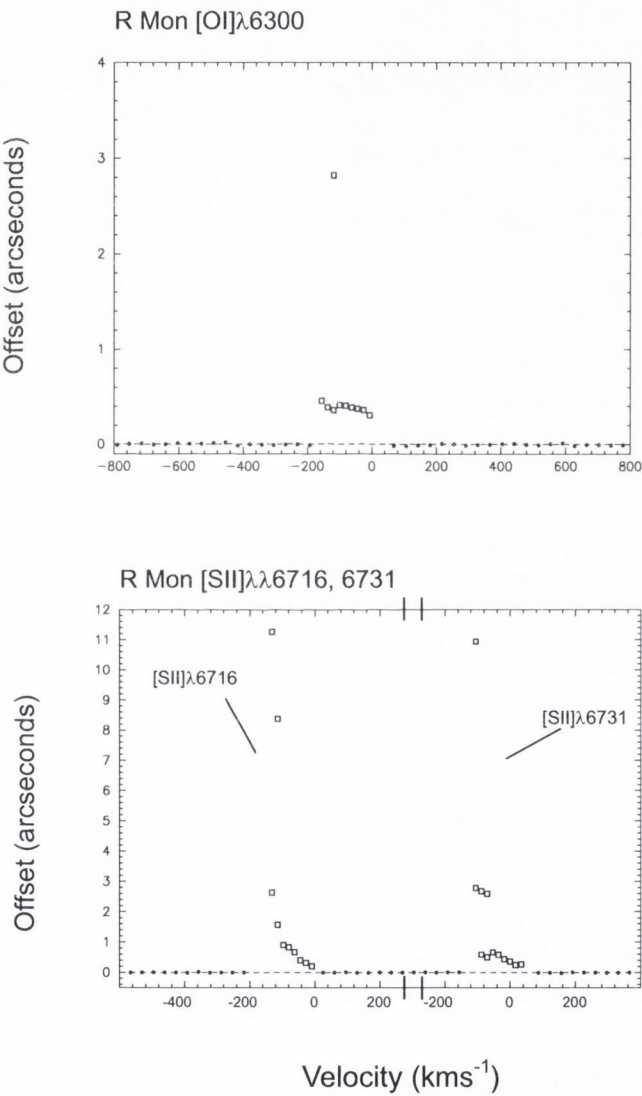


Figure 5.3: Spectro-astrometric plots for the extended outflow from R Mon in [OI]λ6300 and [SII]λλ6716,6731.

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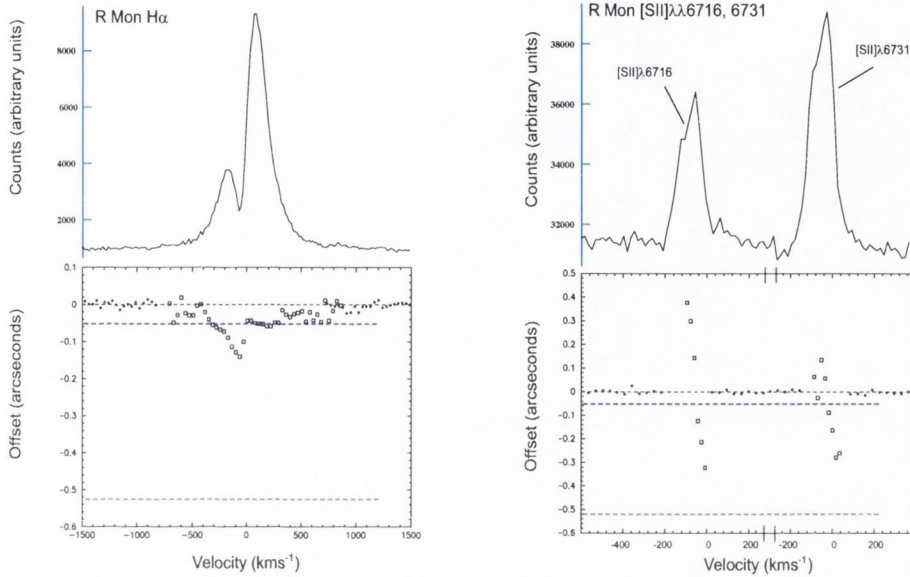


Figure 5.4: Emission line profiles and corresponding spectro-astrometric plots for the H α and [SII] $\lambda\lambda$ 6716,6731 ELRs, near the source. All velocities are LSR velocities and the systemic velocity of R Mon is $\sim +10$ km s $^{-1}$. The blue dashed line marks the position of the near-infrared source and the red dashed line the radio source (3.6cm).

systemic velocity (heliocentric) of R Mon is estimated at $\sim +26$ km s $^{-1}$, (Jones & Herbig, 1982). Hence I estimate the systemic velocity (LSR) to be $\sim +10$ km s $^{-1}$.

As R Mon is deeply embedded it is not seen directly at optical wavelengths but in reflection and the high intrinsic polarisation of the star ($P \sim 13\%$ at a P.A. of $\sim 95^\circ$) supports this idea (Aspin et al., 1985b). Scattering effects are lessened at longer wavelengths hence the position of the star in the near-infrared is closer to its true position and the radio position can be taken as the actual location. It is likely however that the forbidden line emission associated with the blue-shifted outflow is not seen in reflection but directly. This is not uncommon amongst outflows launched by embedded sources (Scarrott, 1988a,b). The position of the FELRs in the spectrum of R Mon measured relative to the continuum is not a measurement of their displacement with respect to R Mon. This explains why the [OI] λ 6300 ELR is offset in a direction opposite to the blue-shifted outflow and the [SII] λ 6731 ELR appears to straddle both sides of the continuum. Close et al. (1997) give the infrared position of R Mon at $0''.06 \pm 0''.02$ south of the optical position and Skinner et al. (1992) estimate the radio position (at 3.6 cm) to be displaced a distance $0''.53$

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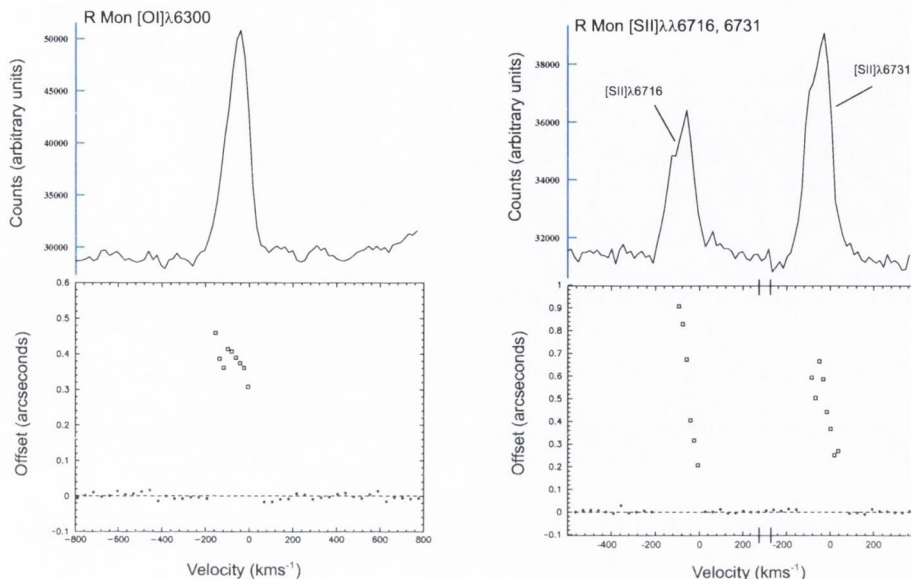


Figure 5.5: Emission line profiles and corresponding spectro-astrometric plots for the $[\text{OI}]\lambda 6300$, $[\text{SII}]\lambda\lambda 6716, 6731$ ELRs, near the source, at a P.A. of 0° for R Mon. All velocities are LSR velocities and the systemic velocity of R Mon is $\sim +10 \text{ km s}^{-1}$. In this figure the position of the ELRs is corrected for the offset of the optical position from the true source position taken from radio observations at 3.6 cm.

away from the optical position, again in a southerly direction. In Figure 5.4 the offset of the $\text{H}\alpha$, $[\text{OI}]\lambda 6300$ and $[\text{SII}]\lambda 6731$ ELRs with respect to the continuum are presented. Marked on these figures are the near-infrared and radio positions of the source. The $\text{H}\alpha$ ELR is seen in reflection unlike the FELRs. In Figure 5.5 the offset of the $[\text{OI}]\lambda 6300$ and $[\text{SII}]\lambda 6731$ ELRs with respect to the position of the radio source are plotted. The $[\text{OI}]\lambda 6300$ and $[\text{SII}]\lambda 6731$ are now displaced in the direction of the blue-shifted flow as expected.

Overall the spatial properties of the FELRs at R Mon (Figure 5.5) compare well to what is seen for the CTTs. Higher velocity emission is clearly offset further from the star than the lower velocity emission and the $[\text{SII}]\lambda\lambda 6716, 6731$ lines are displaced further ($0''.63$) than the $[\text{OI}]\lambda 6300$ line ($0''.41$). The full extent of the flow, observed in $[\text{OI}]\lambda 6300$ and $[\text{SII}]\lambda 6731$ is shown in Figure 5.3. The $\text{H}\alpha$ spectro-astrometric plot is however puzzling. As the majority of the $\text{H}\alpha$ emission originates from the infall onto the star a result showing the $\text{H}\alpha$ ELR coincident with the position of the continuum with the emission from the outflow offset is expected. The bulk of the $\text{H}\alpha$ emission is however offset from the continuum by $\sim 0''.06$ with the emission

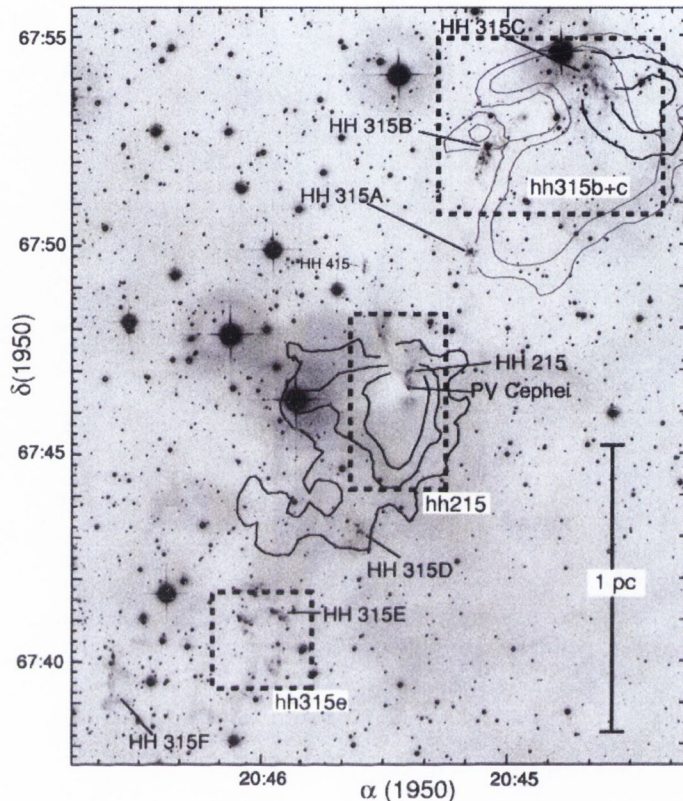


Figure 5.6: Wide field $H\alpha$ + $[SII]$ (optical) CCD image of the HH 315 giant HH flow driven by PV Cephei, taken from Arce & Goodman (2002b). The dashed boxes denote the areas mapped with on-the-fly (OTF) mapping at the IRAM 30m telescope. The name given to each region is shown at the bottom of each region.

at -50 km s^{-1} (the absorption dip) displaced to $\sim 0''.13$. Any interpretation of the $H\alpha$ ELR is greatly complicated by the fact that it is made up of emission from the blue-shifted (and possibly red-shifted) outflow, infall close to the star and by the fact that it is seen in reflection.

5.2.2 PV Cep

PV Cep is a variable star located at the edge of the L1158 and L1155 group of molecular clouds ($d \sim 500 \text{ pc}$) (Cohen, Kuhl, Spinrad, & Harlan, 1981). The presence of a bipolar CO molecular outflow from this source was first reported by Levreault (1984). They put the total length of the flow at 1.5 pc . Neckel, Staude, Sarcander, & Birkle (1987) spectroscopically discovered the HH 215 knots at distance of $25''$ and $60''$ from the source. Six new knots, labelled HH 315 A-F and discovered

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independently by Reipurth et al. (1997) and Gómez, Kenyon, & Whitney (1997) extended the flow length to 2.6 pc (refer to Figure 5.6). The HH 315 flow group of knots are by themselves very interesting. Reipurth et al. (1997) claim that the distances from the source to knots A, B and C are within 10% of the distances from the source to knots D, E and F. Hence it is likely that the six knots come from three major mass ejections. The knots trace a sinusoidal path suggesting that the outflow axis is precessing over time.

This YSO is associated with a bipolar relection nebula similar to R Mon. As PV Cep is located at the edge of its molecular cloud only one lobe of the flow, the southern lobe, is interacting with the parent cloud. The northern (blue-shifted) lobe is outside the cloud and interacts with an environment which is approximately 10 times less dense than the environment south of PV Cep (Arce & Goodman, 2002a,b) (see Figure 5.7). The powerful PV Cep outflow sweeps up the ambient cloud material forming two conical cavities. Starlight is preferentially directed into these cavities and scattering off the walls or dust particles within the cavities produces the observed reflection nebula (Levreault, 1984). Evidence for the presence of a circumstellar disk around PV Cep is presented by van Citters & Smith (1989).

Now considering the outflow close to the source, PV Cep was observed at a P.A. of 25° again in the [OI] $\lambda\lambda 6300, 6363$, [NII] $\lambda 6583$, H α and [SII] $\lambda\lambda 6716, 6731$ lines (Corcoran, 1995; Corcoran & Ray, 1997). The velocities and displacement of the different ELRs are recorded in Table 5.2. The position velocity diagrams, emission line profiles and spectro-astrometric plots are presented in Figures 5.8 and 5.9. The velocities and measured offsets for all the ELRs are recorded in Table 5.2. The systemic velocity is taken at $+ 2.5 \text{ kms}^{-1}$ (Arce & Goodman, 2002a). The [OI] $\lambda\lambda 6300, 6363$ and [SII] $\lambda\lambda 6716, 6731$ are double peaked and the [NII] $\lambda 6583$ line is only weakly detected. As is clear from Figure 5.9 the [OI] $\lambda 6300$ HVC is offset further from the source than the LVC. The [SII] $\lambda\lambda 6716, 6731$ ELRs are weaker than the [OI] $\lambda 6300$ ELR, especially the [SII] $\lambda 6716$ line hence it was only possible to study the HVC. Note that the [SII] $\lambda\lambda 6716, 6731$ ELRs are displaced to a greater extent than the [OI] $\lambda 6300$ line. The [NII] $\lambda 6583$ line is also offset further from the star than the [OI] $\lambda 6300$ line. All offsets in the FELRs are blue-shifted indicating the presence of a disk. All these features of the spatial properties of the PV Cep FELRs indicate that activity close to the central engine of this Herbig Ae/Be star is similar to activity in CTTs.

The H α emission line profile of PV Cep is quiet complicated and requires some

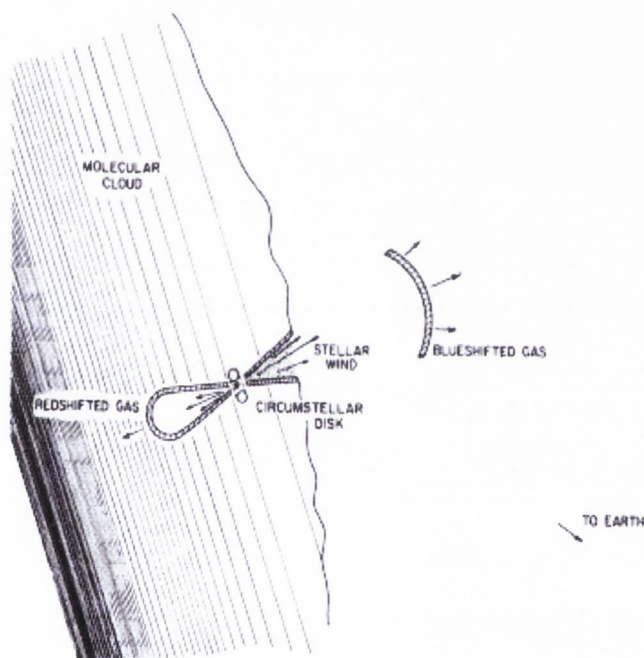


Figure 5.7: A model for the PV Cep system, presented by Levreault (1984). The southern red-shifted lobe of the outflow is directed into the cloud and the blue-shifted lobe outwards into a less dense medium. The red and blue-shifted lobes are asymmetric and this asymmetry is easily explained by the fact that they interact with material of widely differing densities. Scattering within the resulting cavities causes the observed reflection nebula which is shaded in the above illustration.

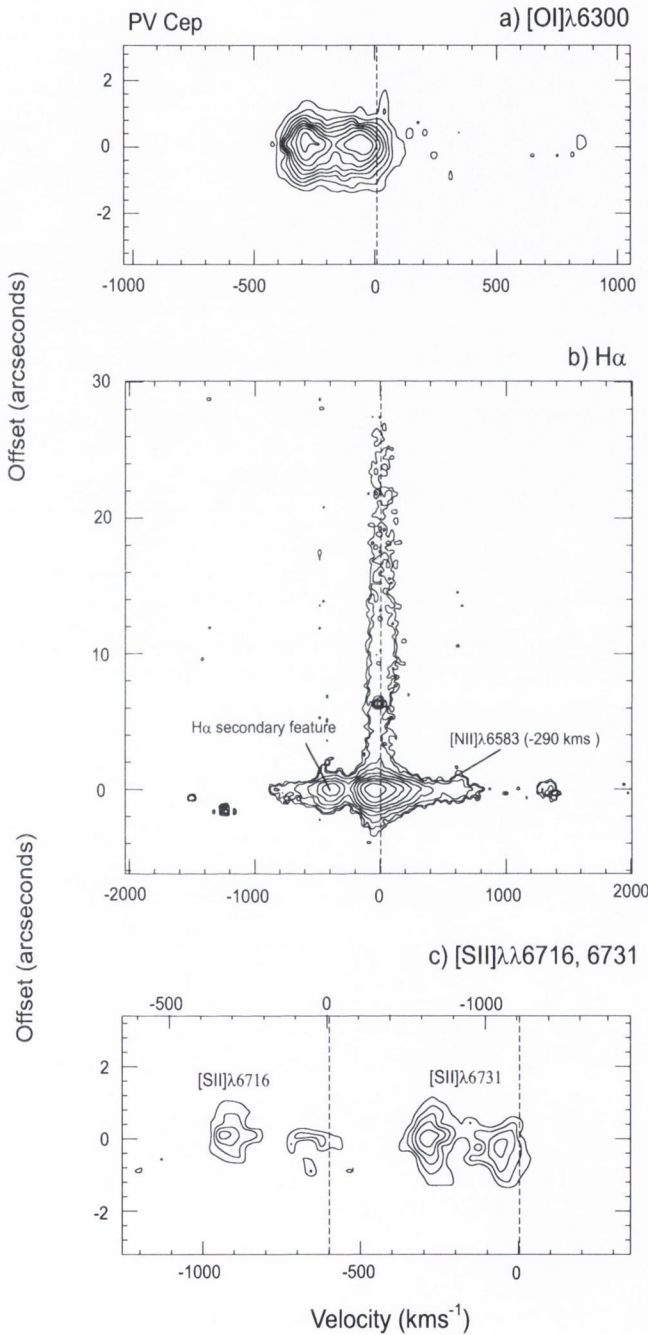


Figure 5.8: Position velocity diagrams of the [OI]λ6300, Hα and [SII]λλ6716,6731 ELRs at PV Cep. Contours begin at the 3σ above the background noise and increase by factors of $\sqrt{2}$. All velocities are LSR velocities. For the [SII]λλ6716,6731 ELRs the velocity scale for the [SII]λ6731 line is marked along the bottom of the position velocity diagram and the scale for the [SII]λ6716 is marked along the top. The dashed line indicates the systemic velocity.

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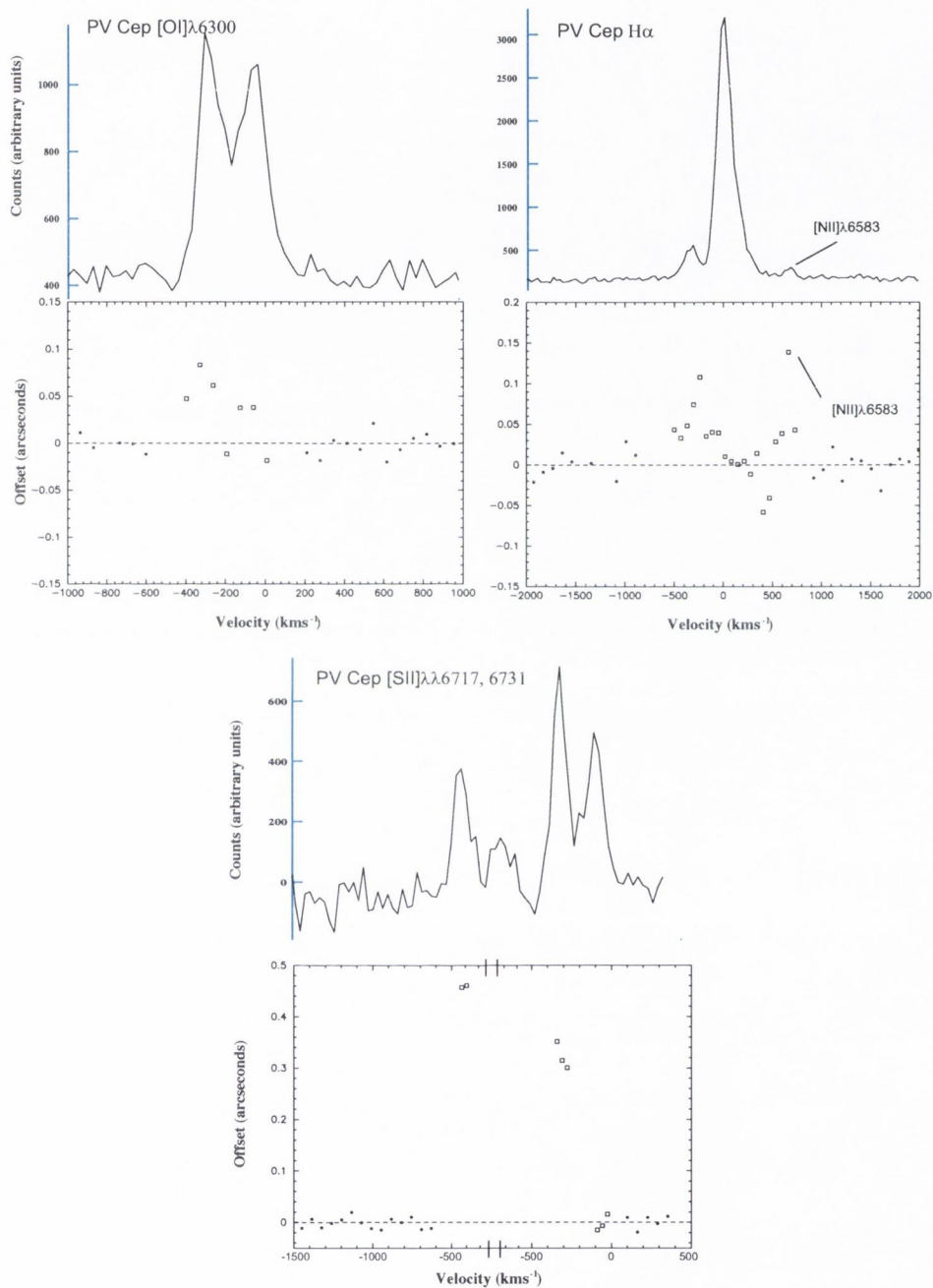


Figure 5.9: Emission line profiles and corresponding spectro-astrometric plots for the H α and [SII] $\lambda\lambda$ 6716,6731 ELRs, at the source, at a P.A. of 25° for PV Cep. The velocity resolution for these observations was larger than for all the other sources, 65 km s⁻¹ at H α compared to 36 km s⁻¹, hence the ELRs are less finely sampled. Note the red-shifted displacement in the H α line wing.

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explanation. The bulk of the emission is centred at $\sim 15 \text{ kms}^{-1}$ and the red-wing extends to $+500 \text{ kms}^{-1}$. An absorption feature and a small secondary peak at $\sim -345 \text{ kms}^{-1}$ is observed in the blue wing. I measure a blue-shifted offset of $\sim 0''.1$ which corresponds to the secondary peak and very interestingly a red-shifted offset of $\sim -0''.06$ in the red-wing. I propose that the red-wing originates in the red-shifted outflow and that a dust hole in the circumstellar disk of PV Cep is allowing the detection of the red-shifted flow at this wavelength, where it is obscured by the disk in the FELs. This is identical to results presented for V536 Aql in Chapter 4. I shall further discuss the red-shifted offset in the $\text{H}\alpha$ line-wing in Section 5.3.3. Also note that there is a blue-shifted displacement in the $\text{H}\alpha$ spectro-astrometric plot which is the $[\text{NII}]\lambda 6583$ line at $\sim -60 \text{ kms}^{-1}$.

5.2.3 V645 Cygni (The Duck Nebula)

While there is no shortage of data describing this source, the true nature of the activity surrounding V645 Cygni still remains an interesting puzzle. V645 Cyg lies in the Cassiopeia-Perseus spiral arm at a distance of $\sim 3.5 \text{ kpc}$. It is a deeply embedded, highly luminous source that was first observed optically from the ground by Cohen (1977). Cohen (1977) described it as a YSO and presented spectrophotometric and spectro-polarimetric data on three knots which he labelled N0, N1 and N2 (see Figure 5.10). He concluded that it lies within a reflection nebula, named the Duck nebula by Goodrich (1986b) and that it has a high degree of optical polarisation 13% at a P.A of 135° . Hence we are seeing this source, entirely in scattered light (Minchin, Hough, Burton, & Yamashita, 1991).

This region contains many signposts of star formation. A poorly collimated CO molecular outflow is known to exist. The axis of this flow, is aligned in a roughly northwest-southeast direction with the blue-shifted outflow towards the south (Rodríguez, Torrelles, & Moran, 1981; Torrelles et al., 1987; Schulz et al., 1989; Verdes-Montenegro et al., 1991). Goodrich (1986b) detected a bright $[\text{SII}]$ knot directly south of N1, which he concludes is a HH object, however it is not recorded whether this knot is blue or red-shifted. Also images of the Duck Nebula reveal a long narrow feature which he refers to as “the beak”. It is directed north from N0 and the above author suggests that it may possibly be the remnant of a jet. All these features are marked in Figure 5.10.

Cohen (1977) was the first to refer to the FELs present in the optical spectrum

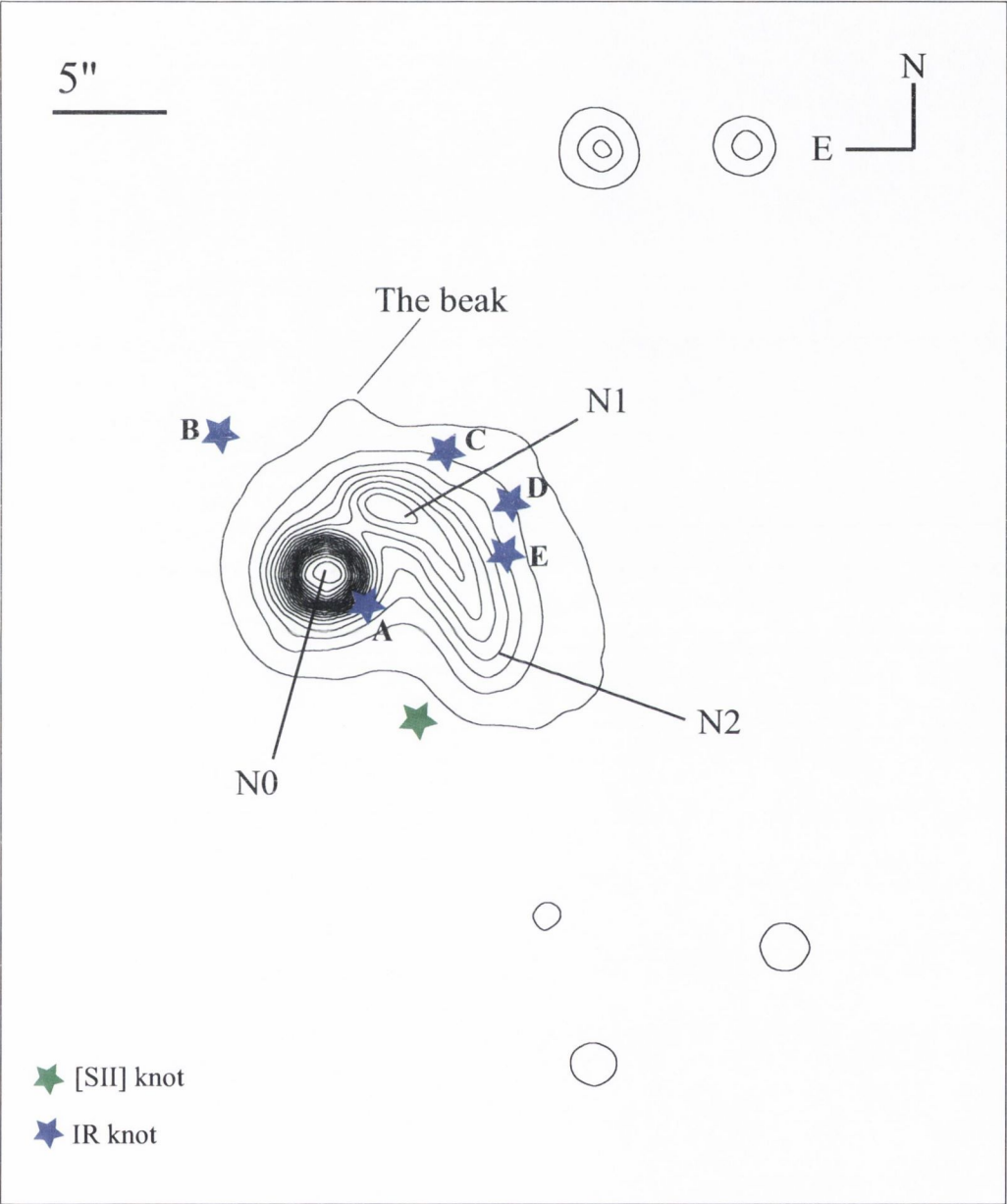


Figure 5.10: SII contour map of the region immediately surrounding V645 Cygni. Knots N0, N1 and N2 are clearly marked as well as the [SII] knot discovered by Goodrich (1986b). Knot N2 is however much weaker than either N0 or N1 hence it is not clearly seen in this image. Also marked are the H_2 features observed by Corcoran (1995). This image was taken using the Wide Field Camera (WFC) on the INT (McGroarty et al., 2004a).

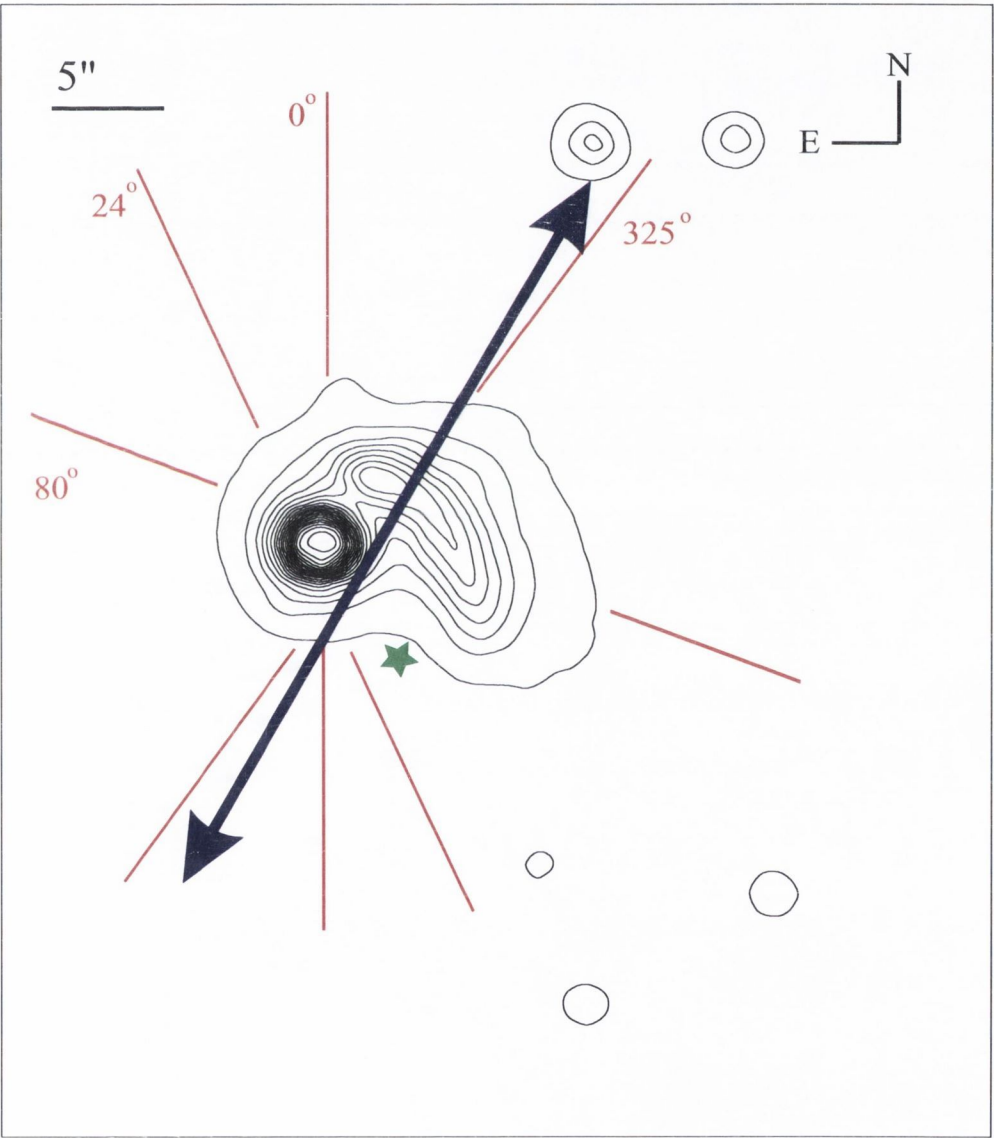


Figure 5.11: [SII] contour map of the region immediately surrounding V645 Cyg. This figure illustrates the different P.A.s at which the observations were taken highlighting the position of the slit with respect to N0 and N1 in each case. The blue arrow is the predicted orientation of the outflow based on results discussed here.

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of V645 Cyg and Hamann & Persson (1989) noted the double peaked nature of the [SII] $\lambda\lambda 6716, 6731$ ELRs and compared these results to what was then known for the CTTSs. The implications of the multi-component nature of [OI] $\lambda 6300$ line were later studied by Corcoran & Ray (1997). There are still questions regarding the true nature of knots N0 and N1. It is suggested that they are reflection spectra of the same central object viewed from different positions (Hamann & Persson, 1989). However Corcoran (1995) presents FEL spectra which he argues demonstrates that N0 and N1 are in fact two separate sources driving two separate bipolar outflows. I further discuss this problem in section 5.3.2.

Applying the technique of spectro-astrometry to the optical spectra presented by the above author allowed me to get a somewhat clearer picture of the outflow activity in the vicinity of this YSO. The optical forbidden emission from this source was observed at four PAs, namely 0° , 24° , 80° and 325° (Figure 5.11) and I mapped the [SII] $\lambda\lambda 6716, 6731$ and $H\alpha$ ELRs at all the above PAs. Only at a PA of 24° was the [OI] $\lambda\lambda 6300, 6363$ emission detected as it was only for this observation that the wavelength coverage reached this part of the spectrum. At P.A.s of 0° and 24° the slit intersects knot N0 only but at 80° and 325° N1 is also observed. The position velocity diagrams of each ELR are presented in Figure 5.12 and Figure 5.13. I present the [SII] $\lambda\lambda 6716, 6731$ and $H\alpha$ spectro-astrometric plots and emission line profiles in Figures 5.14 to 5.17.

I firstly wish to discuss the $H\alpha$ emission. The N1 $H\alpha$ ELR at a P.A. of 80° and 325° also includes the [NII] $\lambda 6548$ and [NII] $\lambda 6583$ FELs. I measured the displacement in all three lines and I produced essentially the same result at both P.A.s. The $H\alpha$ blue-shifted outflow component is offset to a greater extent than the [NII] emission in both cases and the [NII] $\lambda 6583$ ELR is displaced further than the weaker [NII] $\lambda 6548$ line. The velocities at which the displacements occur and the extent of the offsets are similar at both P.A.s (Table 5.2). At 80° and 325° no [NII] emission is observed at N0 and the measured offset in the $H\alpha$ ELR are random, with scatter in the wings of the $H\alpha$ line and a tightening in position at the line centre. The scatter is consistent with the smaller number of counts in the line wings than at the line centre and continuum.

Most interestingly the $H\alpha$ ELR at N0, at 0° and 24° is very similar to what I observe at N1, in that the [NII] $\lambda 6548$ and [NII] $\lambda 6583$ emission lines are distinctly visible, as well as the blue-shifted jet component in $H\alpha$. The [NII] lines are not detected at the source as in the case of knot N1 but at $1''.5$ to $2''.5$ from the source.

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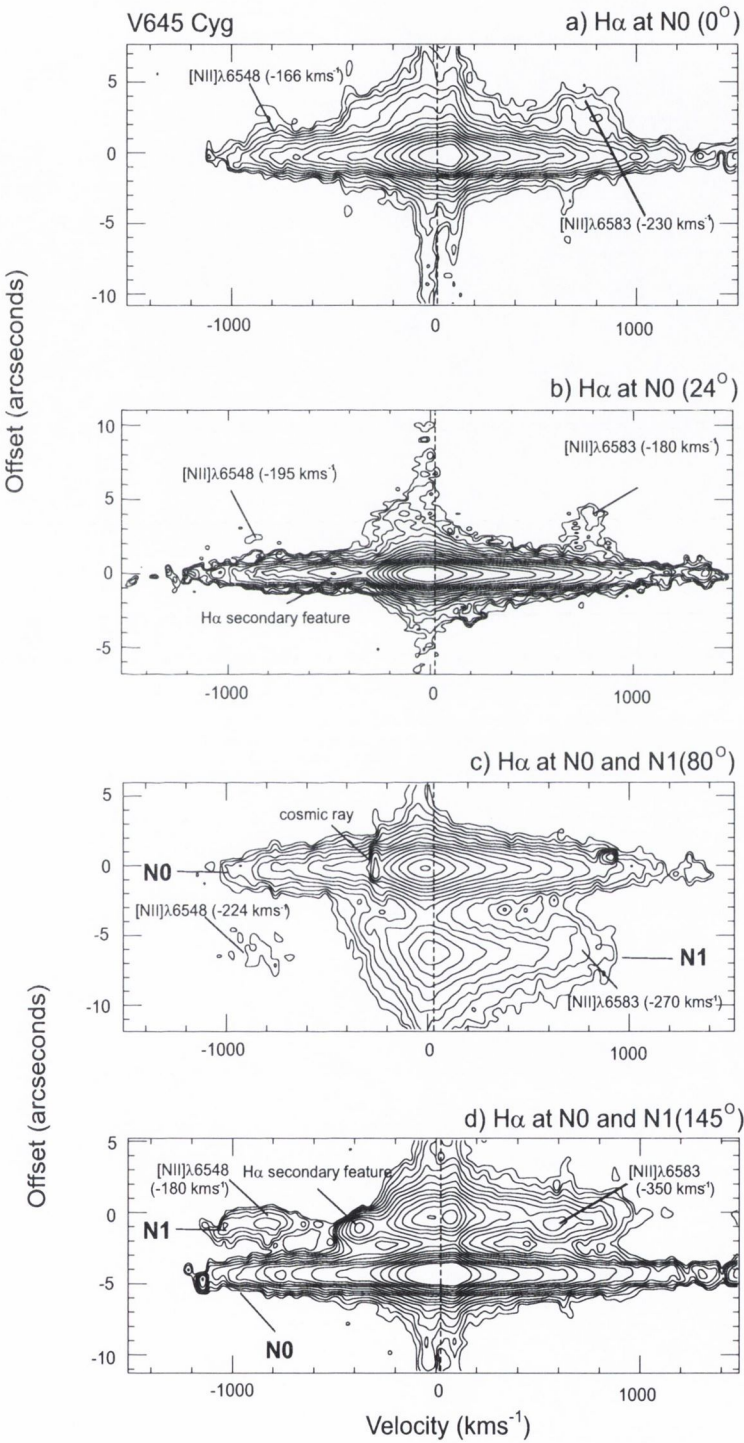


Figure 5.12: Position velocity diagrams of the H α ELR at P.A.s of 0° , 24° , 80° and 325° for V645 Cyg. Knots N0 and N1 are observed at 80° and 325° . Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. All velocities are LSR velocities. The dashed line indicates the systemic velocity

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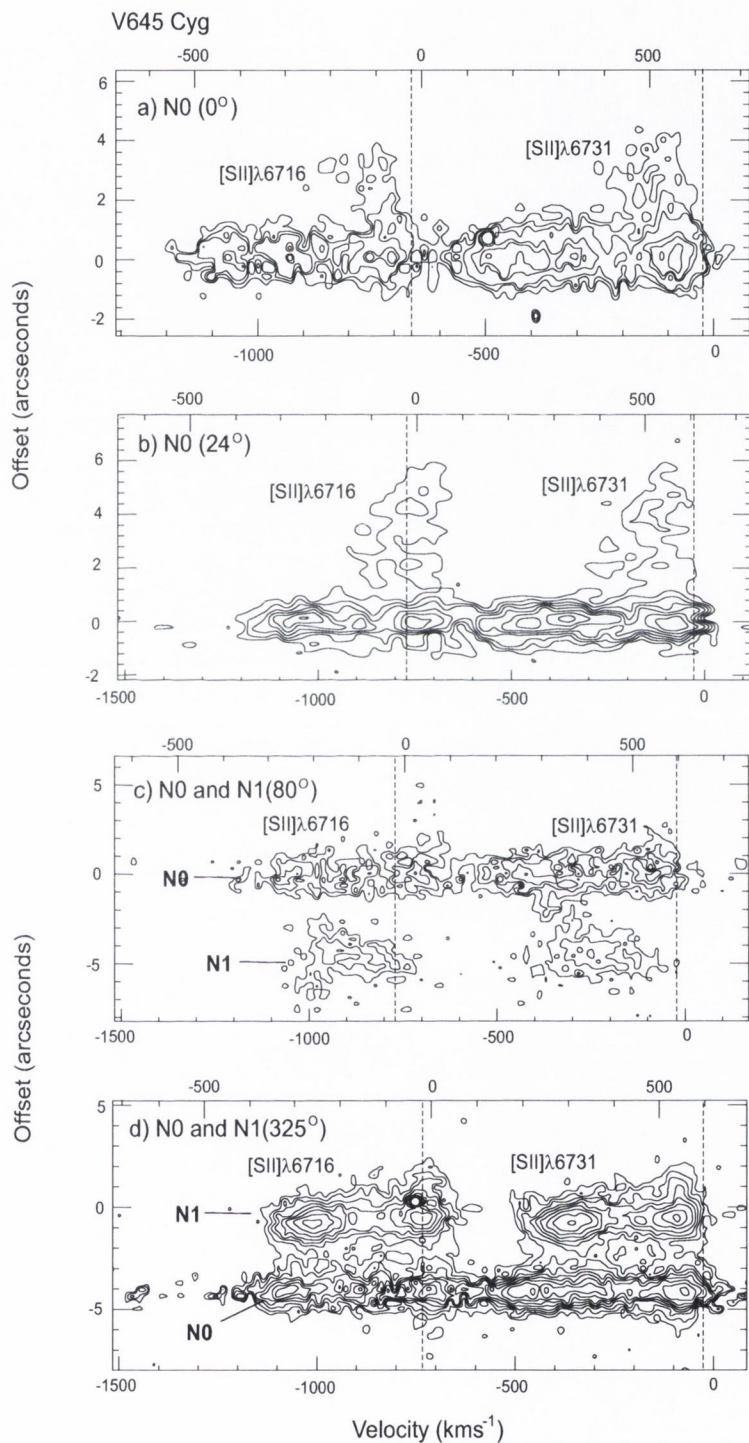


Figure 5.13: Position velocity diagrams of the $[\text{SII}]\lambda\lambda 6716, 6731$ ELRs at P.A.s of 0° , 24° , 80° and 325° for V645 Cyg. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. All velocities are LSR velocities. The velocity scale for the $[\text{SII}]\lambda 6731$ line is marked along the bottom of each diagram and the scale for the $[\text{SII}]\lambda 6716$ along the top. The dashed line indicates the systemic velocity.

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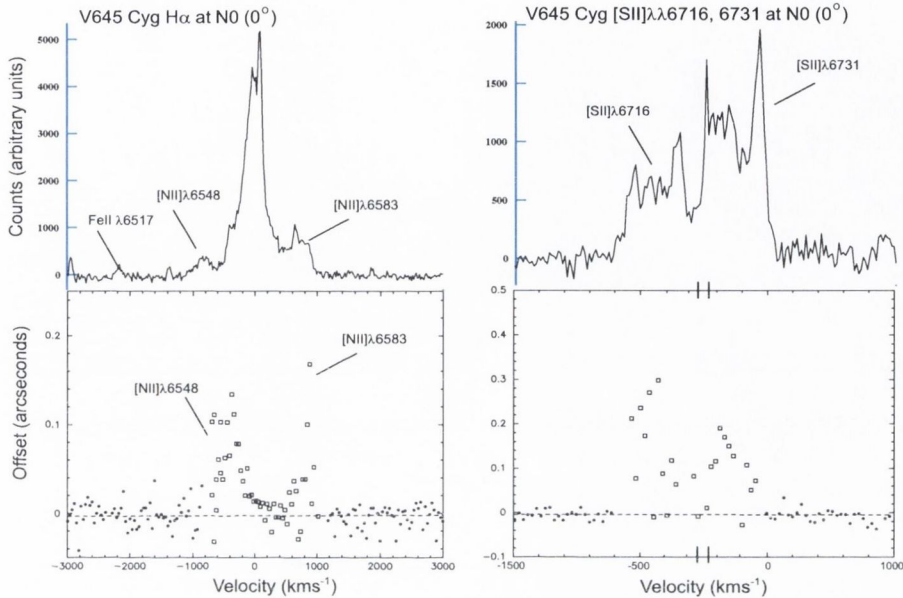


Figure 5.14: Emission line profiles and corresponding spectro-astrometric plots for the H α and [SII] $\lambda\lambda$ 6716,6731 ELRs, at a P.A. of 0° for V645 Cyg. Only knot N0 is observed at 0° . All velocities are LSR velocities.

The [NII] emission is at the shorter distance at 0° , hence emission at the source is influenced strongly by the presence of these ELRs and appears to be offset in their direction. This is obvious in Figure 5.14. Here the pattern of displacement (but not the magnitude or direction) is the same as seen for N1. The secondary H α peak is offset to $\sim 0''.1$ at a comparable velocity to where I see this feature at N1 (see Table 5.2). At 24° the blue-shifted jet component to the H α line is offset at the source, again to $\sim 0''.1$. The [NII] ELRs are at too great a distance to have the same effect on emission at the source as seen for 0° .

At 325° the [SII] $\lambda\lambda$ 6716,6731 emission from N0 and N1 appears to be almost identical, in velocity. I measure the LVC and HVC at N0 and N1 at approximately -78 km s^{-1} and -356 km s^{-1} and -80 km s^{-1} and -374 km s^{-1} respectively. The low and high velocity emission is observed at similar velocities at the other P.A.s however it is only at 325° that the slit passes *directly* through both knots. The displacement in the [SII] $\lambda\lambda$ 6716,6731 ELR at N0 is on the same scale at all PAs but strongest at 325° and again velocities are comparable. The position velocity diagrams of the [SII] $\lambda\lambda$ 6716,6731 emission at 0° and 24° show that the extension in

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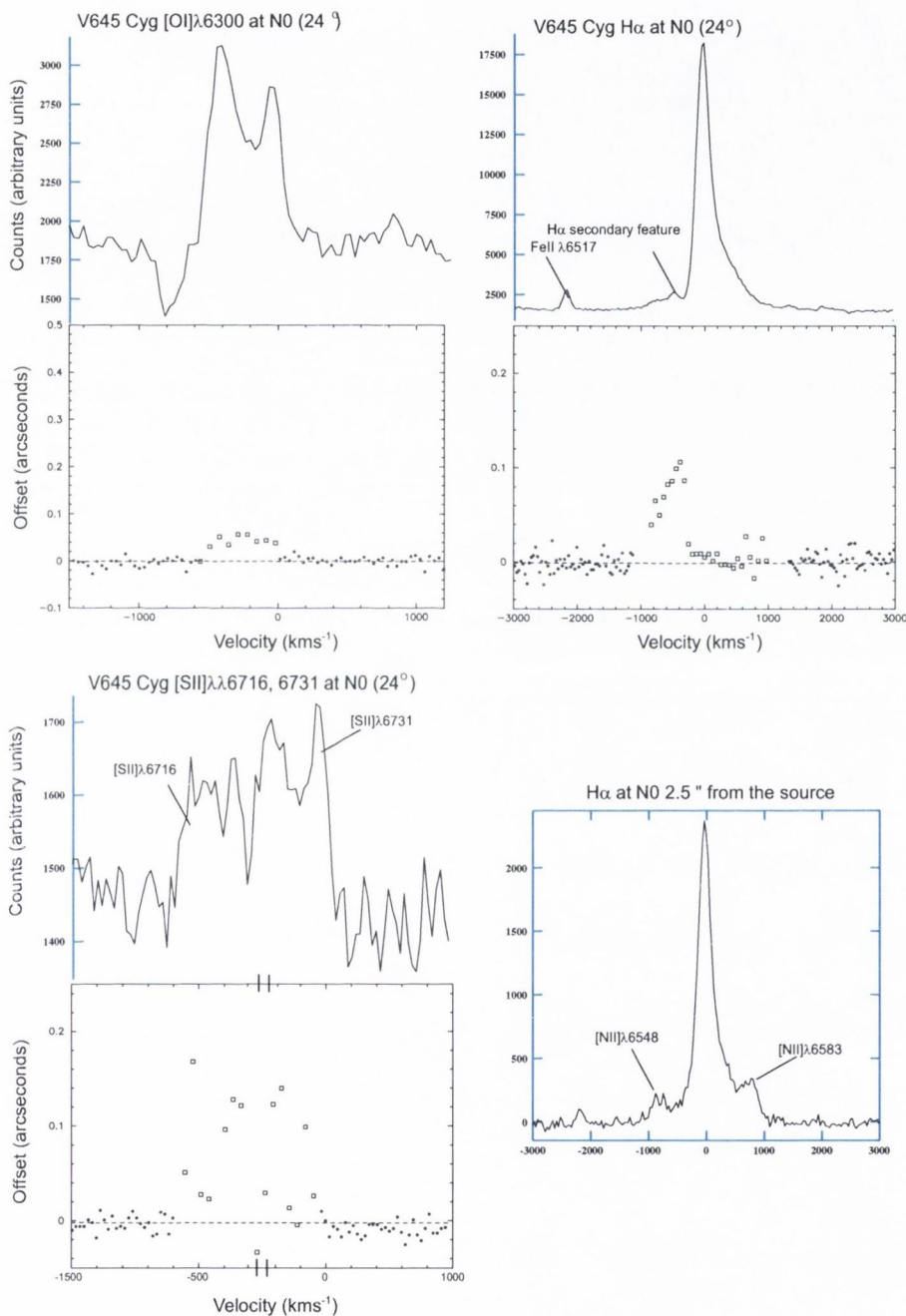


Figure 5.15: Emission line profiles and corresponding spectro-astrometric plots for the H α , [SII] $\lambda\lambda$ 6716,6731 and [OI] λ 6300 ELRs, at a P.A. of 24° for V645 Cyg. Only knot N0 is observed at 24° . All velocities are LSR velocities. The emission line profile of the H α region taken at $\sim 2''.5$ from the source highlights the presence of [NII] emission at this position.

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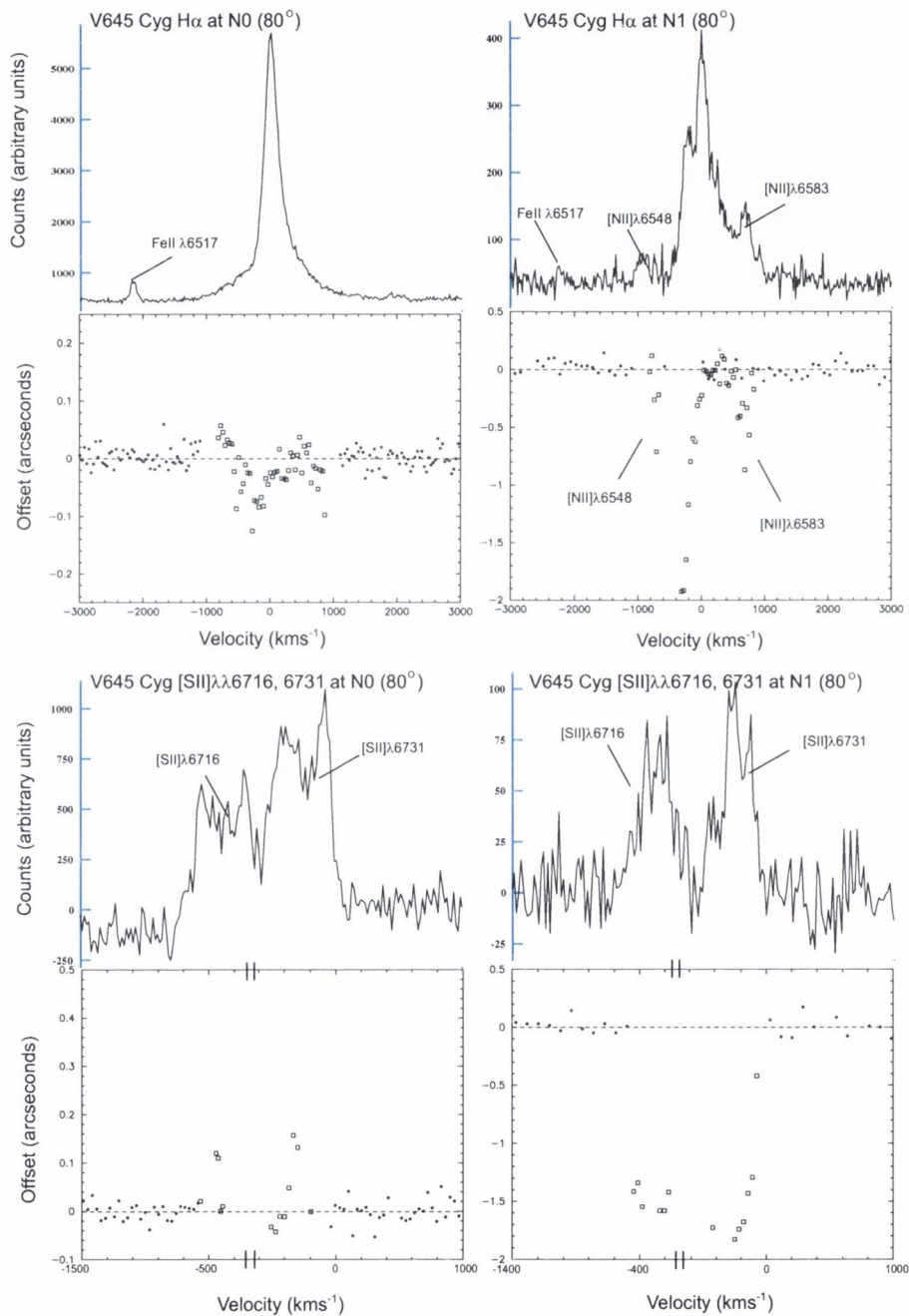


Figure 5.16: Emission line profiles and corresponding spectro-astrometric plots for the H α and [SII] $\lambda\lambda 6716, 6731$ ELRs, at a P.A. of 80° for V645 Cyg. Both N0 and N1 are observed at 80° . All velocities are LSR velocities.

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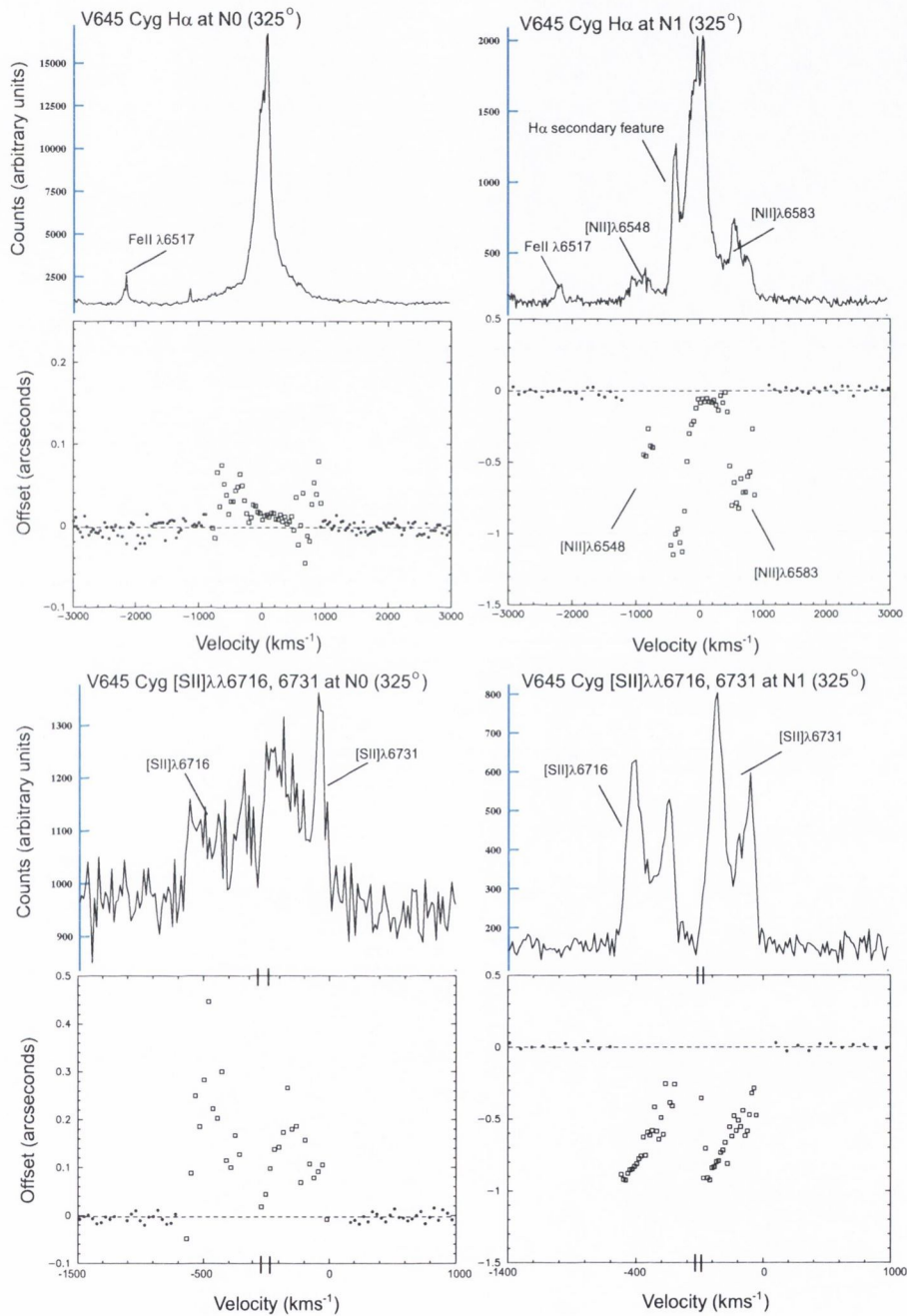


Figure 5.17: Emission line profiles and corresponding spectro-astrometric plots for the H α and [SII] $\lambda\lambda$ 6716,6731 ELRs, at a P.A. of 325° for V645 Cyg. Both N0 and N1 are observed at 325°. All velocities are LSR velocities.

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the outflow is observed at these P.A.s. The same similarities are evident between the [SII] $\lambda\lambda 6716, 6731$ ELRs at N1 at 80° and 325° . An overall comparison between the position spectra for N0 and N1 reveals that the [SII] $\lambda\lambda 6716, 6731$ emission at N1 at all P.A.s, is offset in the opposite direction (towards the position of N0) and to a much greater extent ($0''.4$ as compared to $\sim 1.5''$) than the emission at N0. Only blue-shifted emission is observed confirming the presence of a circumstellar disk. Other important points to note are firstly that the [OI] $\lambda 6300$ ELR at N0 at 24° is displaced at a similar velocity to the [SII] $\lambda\lambda 6716, 6731$ lines but the displacement is smaller. This is due to the higher critical density of the [OI] $\lambda 6300$ line and is to be expected. Secondly in all cases the high velocity emission is offset further than the source than the low velocity component of the ELR. This is in line with what is observed for the CTTSs. Thirdly the [SII] $\lambda\lambda 6716, 6731$ emission at N1 is not traced all the way back to the source but offsets begin at $\sim 0''.25$ from the source.

5.2.4 LkH α 233

LkH α 233 is an A5/A4 intermediate mass star (Corcoran & Ray, 1997; Hernández et al., 2004) which was first identified as a Herbig Ae/Be star by Herbig (1960). One of the most striking features of this source is the X-shaped bipolar nebula (~ 0.1 pc in size) with which it is associated (Herbig, 1960; Calvet & Cohen, 1978). Observations made in the near-infrared using speckle interferometry detected the presence of a light scattering halo of $\sim 1''$ in size and with a polarisation greater than 10 (Leinert, Haas, & Weitzel, 1993). Hence it is likely as suggested by Leinert, Haas, & Weitzel (1993) that LkH α 233 is a deeply embedded object which is optically visible mostly in scattered light.

Corcoran & Ray (1998b) presented the first evidence for an extended outflow from this young star. They detected the presence of a bipolar outflow spectroscopically, in the [OI] $\lambda 6300$ and [SII] $\lambda\lambda 6716, 6731$ optical FELs. Interestingly the blue-shifted jet could be traced closer to the driving source than the red-shifted counter-jet. Also the low velocity component which is detected in the blue flow is not visible in the red. All this points to the presence of a circumstellar disk which is obscuring the red-shifted flow close to the source, as is seen in the T-Tauri stars. Corcoran & Ray (1998b) estimate an upper limit for the projected radius of the disk of ~ 600 AU, based on the angular separation of the stellar photocentre to the edge of the counter-jet. McGroarty et al. (2004a) presented the first optical

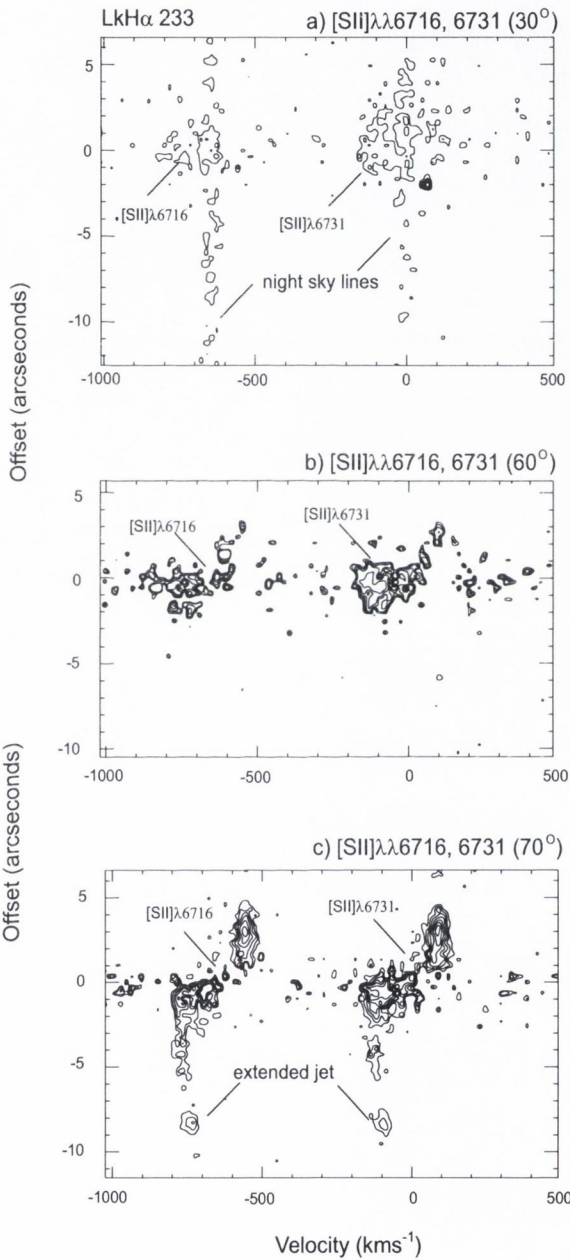


Figure 5.18: Position velocity diagrams of the [SII] $\lambda\lambda 6716, 6731$ ELRs at LkH α 233 at P.A.s of 30°, 60° and 70°. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. All velocities are LSR velocities. Note that the extended outflow is only seen at 70°.

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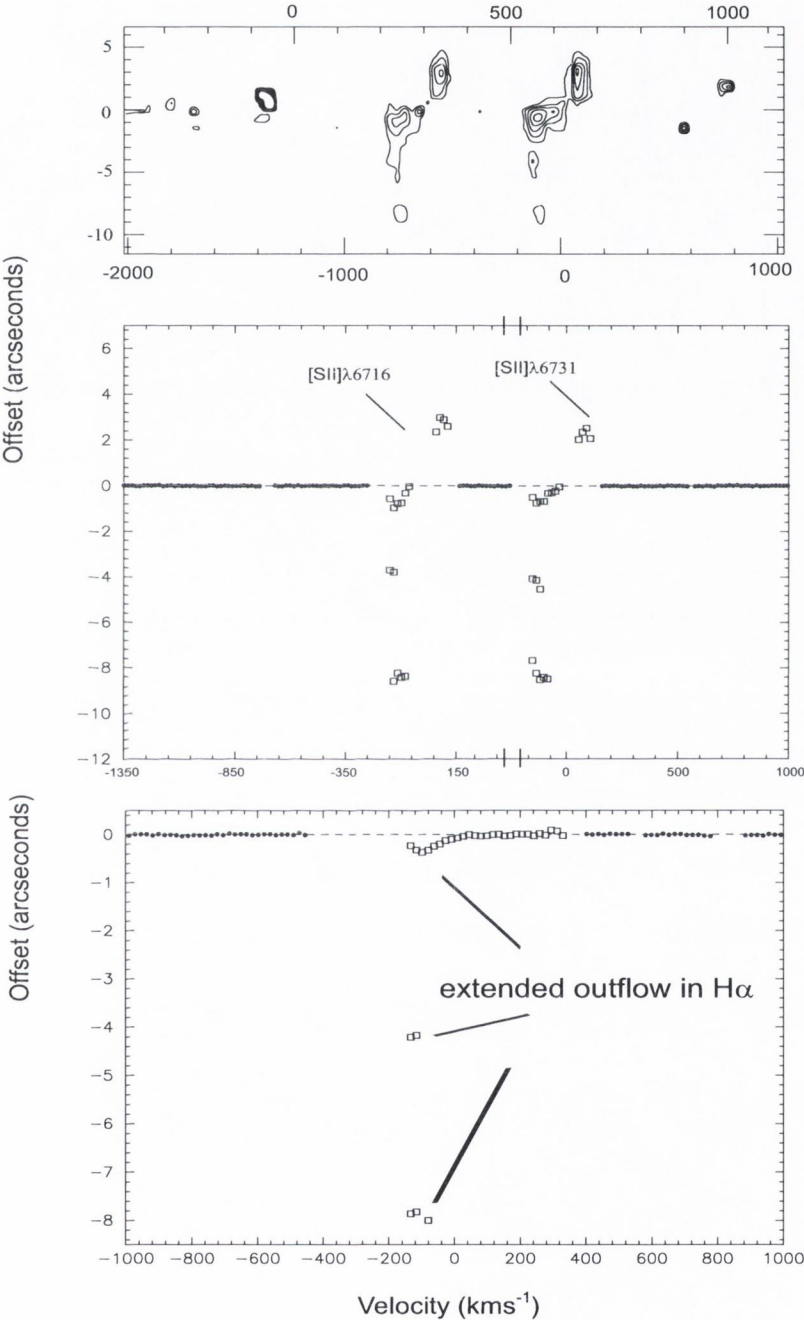


Figure 5.19: Position velocity diagram of the [SII]λλ6716,6731 ELRs at LkHα 233 at 70° and the Hα and [SII]λλ6716,6731 spectro-astrometric plots. Note how the jet can easily be traced to ~ 10". The extended jet is also only seen in Hα at 70°. At all other angles the outflow at the source is represented by an offset in the blue-wing of the Hα line profile.

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images of the outflow from LkH α 233. In the jet direction they detected a $\sim 7''$ jet at a P.A. of $\sim 248^\circ$ and a series of new Herbig-Haro objects assigned the number HH 808-HH 813. A possible counter-jet is also seen to the northeast of the source however the authors admit that it is difficult to determine whether this is actually part of the flow or a residual of the continuum subtraction process. The HH object HH 814 is also likely to be part of the counter-flow. They put the total length of the outflow at 3.1 pc and the degree of collimation at 6.3° .

Observations were taken at P.A.s of 30° , 60° , 70° and 150° and the spatial properties of the [SII] $\lambda\lambda 6716, 6731$ and H α ELRs were studied for each P.A. Only very weak low velocity [SII] $\lambda\lambda 6716, 6731$ emission is detected at 30° and no forbidden emission only H α at 150° . Corcoran & Ray (1998b) give the P.A. of the outflow as 70° . Figure 5.18 showing the position velocity diagrams of the [SII] $\lambda\lambda 6716, 6731$ emission at 30° , 60° , 70° , also highlights that the outflow is most strongly detected at 70° . Figure 5.19 is a comparison between the spectro-astrometric plot of the [SII] $\lambda\lambda 6716, 6731$ ELRs at 70° with the position velocity diagram. I measured the position of the full extent of the blue and red-shifted flow observed. Three blue-shifted knots are clear and it is also obvious that the red-shifted emission at the source is not detected due to obscuration by the disk, as mentioned above. In Figure 5.22 I plot the displacement of the [SII] $\lambda\lambda 6716, 6731$ ELRs at 60° and 70° considering only emission closest to the source. Low and high velocity emission is detected although the distinction between the two components is not very clear. The maximum displacement of the emission is the same at both P.A.s, the higher velocity emission is clearly offset further from the source than the lower velocity emission and the [SII] $\lambda 6716$ ELR is displaced further in both cases. For example the [SII] $\lambda 6731$ line is offset to $\sim -0''.8$ at 60° and 70° but at a higher velocity at 70° than 60° , -136 kms^{-1} as opposed to -110 kms^{-1} (see Table 5.2).

The spatial extent of the H α line at all four P.A.s is shown in Figure 5.21. The two knots at $\sim -4''$ and $\sim -8''$ seen in [SII] $\lambda\lambda 6716, 6731$ at 60° and 70° are also detected in H α at 70° , confirming that the outflow axis is orientated at an angle of 70° (see Figure 5.19). Also from Figure 5.21 it is clear that the blue-shifted H α emission close to the source is displaced to the same extent at 30° , 60° and 70° but at a lower velocity and a smaller extent than what is observed in [SII] $\lambda\lambda 6716, 6731$ (-45 to -97 kms^{-1} , $\sim -0''.4$). H α originates much closer to the central star than the [SII] $\lambda\lambda 6716, 6731$ emission, hence a smaller displacement in H α is expected.

Interestingly I also detect a red-shifted displacement in the H α ELR, again at

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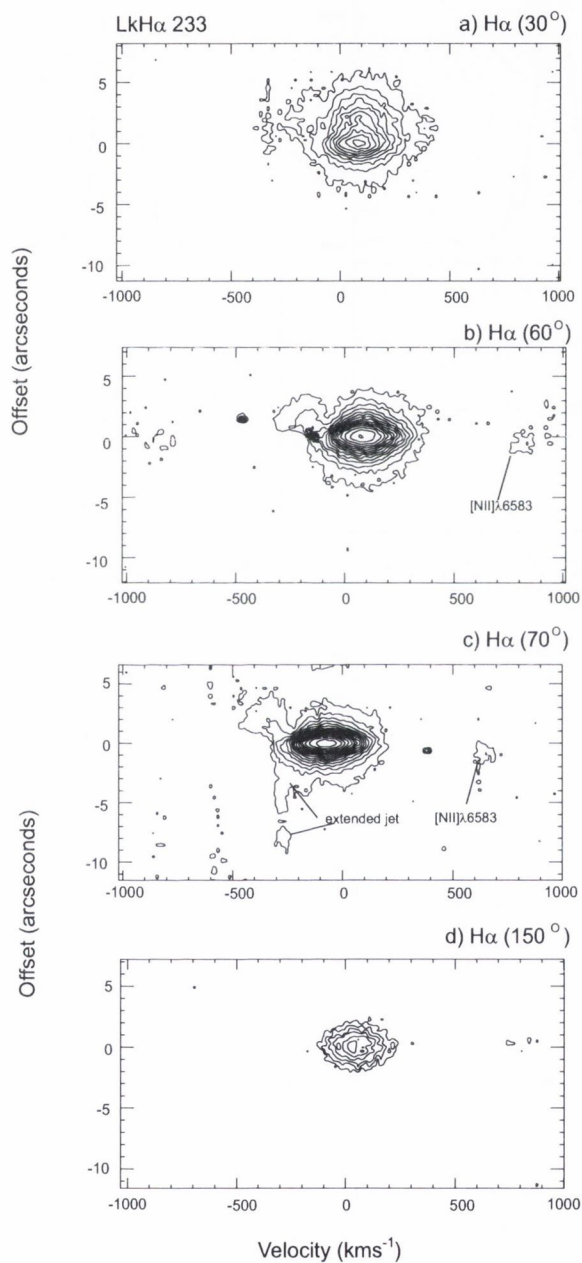


Figure 5.20: Position velocity diagrams of the H α ELR at LkH α 233 at P.A.s of 30°, 60°, 70° and 150°. Contours begin at 3σ above the background noise and increase by factors of $\sqrt{2}$. All velocities are LSR velocities. Note that the extended outflow is only seen at 70° and that the H α line at 150° has no outflow component.

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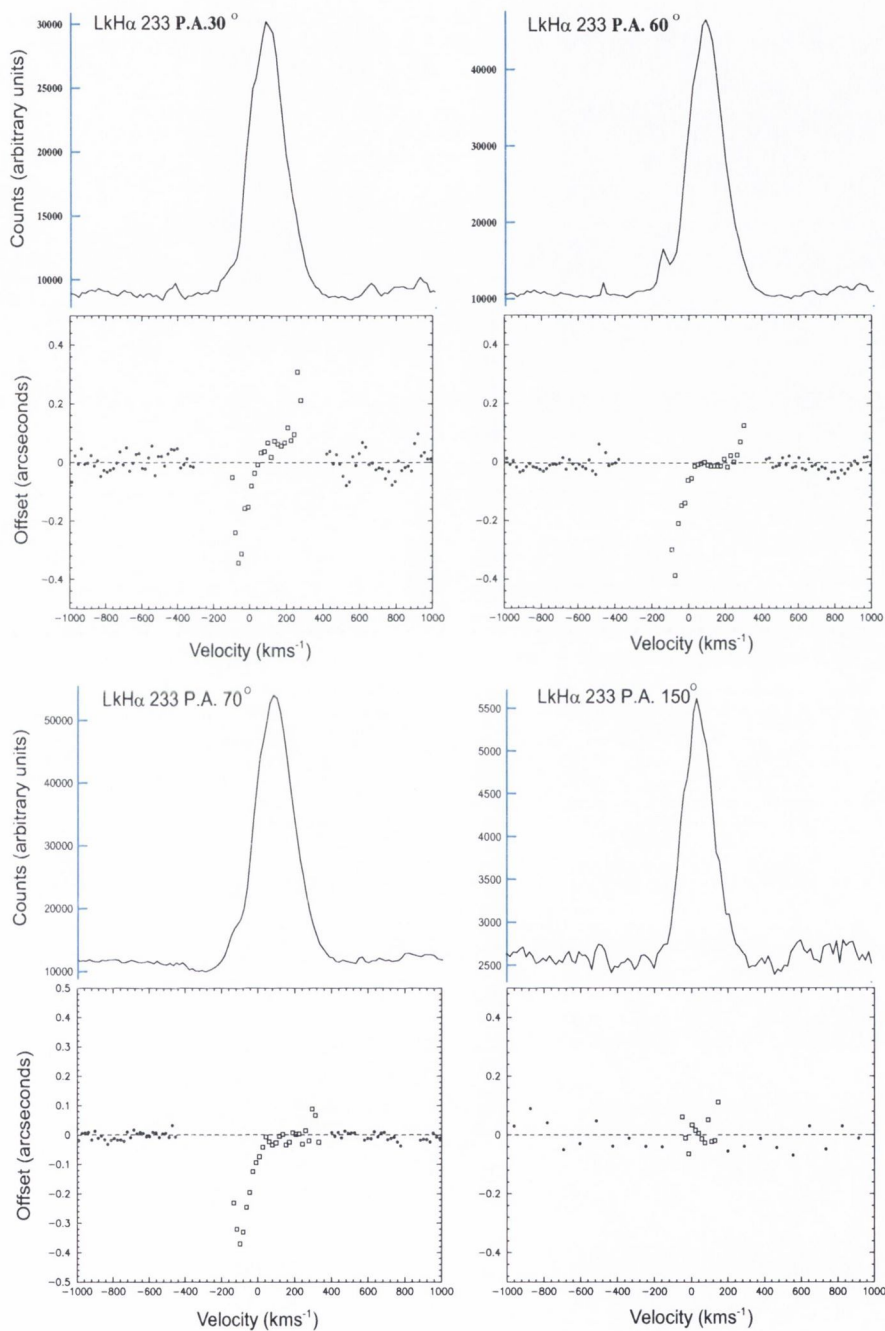


Figure 5.21: Emission line profiles and corresponding spectro-astrometric plots for the H α ELRs, at P.A.s of 30°, 60°, 70° and 150° for LkH α 233. All velocities are LSR velocities. Note the outflow close to the source is displaced to the same extent, in H α at 30°, 60° and 70°. No displacement is measured at 150°. Note also the presence of the red-shifted offsets in the H α red-wing.

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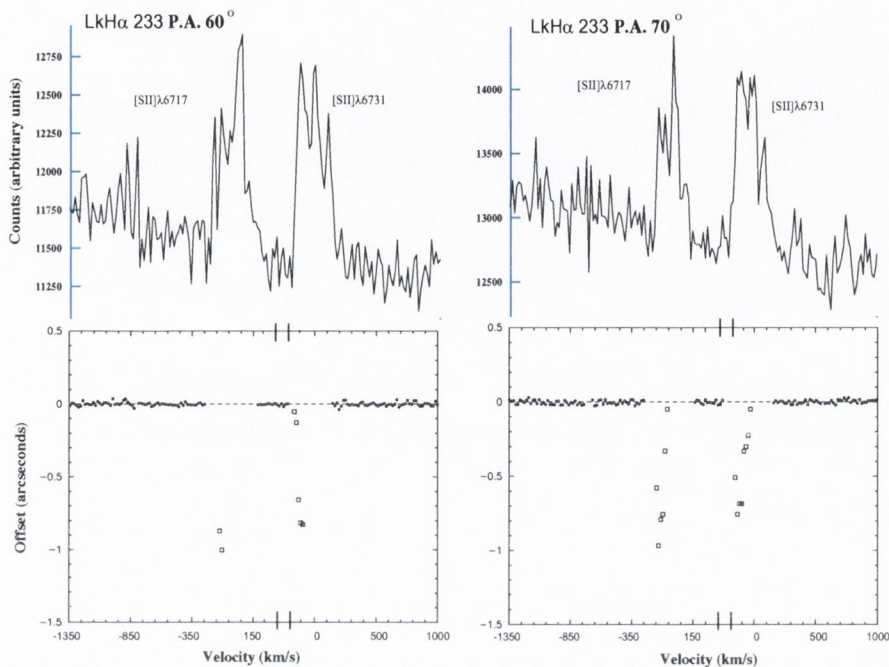


Figure 5.22: Emission line profiles and corresponding spectro-astrometric plots for the [SII] $\lambda\lambda 6716, 6731$ ELRs, at P.A.s of 60° and 70° for LkH α 233. All velocities are LSR velocities.

30° , 60° and 70° . This offset is smallest at 70° and largest at 30° , $0''.088$, $0''.12$ and $0''.33$ for 30° , 60° and 70° respectively. Also this red-shifted offset occurs at a much higher velocity than what I observe for the blue-shifted flow ($260\text{--}300\text{ km s}^{-1}$). The H α ELR overall is quite complicated as is clear from the position velocity diagrams shown in Figure 5.20. As well as observing the extended outflow at 70° I observe a P-Cygni absorption dip at approximately -450 km s^{-1} and a secondary component to the H α line at $\sim -350\text{ km s}^{-1}$. The fact that I observe red-shifted H α emission in the flow so close to the source when I have shown that the red-shifted forbidden emission is obscured by the disk at this distance makes LkH α 233 yet another example of a source where a circumstellar gap or dust hole may be allowing one to observe the red-shifted jet. I further discuss the possibility of such a gap in the disk of this source in section 5.3.3.

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Object	Emission Line	$V(\text{kms}^{-1})$	Offset($''$)
R Mon	$\text{H}\alpha$	-160, 95	
	[OI] λ 6300	-45; -140*	0.41; 2.8*
	[SII] λ 6731	-30; -104*	0.63; 3*, 11*
PV Cep	$\text{H}\alpha$	-250; 400	0.11; -0.06
	[OI] λ 6300	-320(H); -60(L)	0.08; 0.04
	[SII] λ 6731	-300(H); -56(L)	0.3; 0.02
V645 Cyg (0°) N0	$\text{H}\alpha$	-370	0.1
	[NII] λ 6583	-230	0.17
	[SII] λ 6731	-380(H); -80(L); -230*	0.2; 0.07; 3*
V645 Cyg (24°) N0	$\text{H}\alpha$	-380	0.11
	[OI] λ 6300	-400(H); -80(L)	0.055; 0.04
	[NII] λ 6583	-180	2.5
V645 Cyg (80°) N0	[SII] λ 6731	-380(H); -75(L); -160*	0.14; 0.06; 3.2*
	[SII] λ 6731	-360(H); -85(L)	0.16
	$\text{H}\alpha$	-315	-1.9
V645 Cyg (80°) N1	[NII] λ 6583	-270	-0.87
	[SII] λ 6731	-250(H)	-1.8
	[SII] λ 6731	-356(H); -78(H)	0.25; 0.4
V645 Cyg (325°) N1	$\text{H}\alpha$	-420	-1.15
	[NII] λ 6583	-350	-0.8
	[SII] λ 6731	-374(H); -80(L)	-0.8; -0.3
LkH α 233 (30°)	$\text{H}\alpha$	-60; 260	-0.34; 0.3
LkH α 233 (60°)	$\text{H}\alpha$	-75; 300	-0.4; 0.12
	[SII] λ 6731	-110	-0.8
LkH α 233 (70°)	$\text{H}\alpha$	-97; -115*; 290	-0.37; -8*, -4*; 0.09
	[SII] λ 6731	-136	-0.76

Table 5.2: Table comparing peak LSR velocities and offsets measured for each source in $\text{H}\alpha$, [OI] λ 6300, [NII] λ 6548 or [SII] λ 6731, at each P.A. that was observed.

* More than one knot is seen at this emission line and the velocity and position of these extended knots are given.

5.3 Discussion

5.3.1 Using the Disk Wind Model to Describe the FELRs of Herbig Ae/Be stars

Very early spectroscopic studies of pre-main sequence objects, in particular the TTSs, reported the dominant presence of blue-shifted optical FELs ([OI] $\lambda\lambda$ 6300,6363 and [SII] $\lambda\lambda$ 6716, 6731) (Cohen & Kuhl, 1979; Jankovics et al., 1983; Appenzeller, Östreicher, & Jankovics, 1984; Edwards et al., 1987). Jankovics et al. (1983) were the first to associate the FELRs of TTS with mass outflow. Since then much progress has been made regarding the understanding of forbidden emission from CTTSs and in particular their multi-component nature. This is much discussed in Chapters 1, 2 and 3. As mentioned above far fewer Herbig Ae/Be stars than CTTSs are known to have blue-shifted forbidden emission and even fewer blue-shifted multi-component forbidden emission. However Corcoran & Ray (1997) did report that some 50% of the Herbig Ae/Be stars with [OI] λ 6300 emission they studied, had asymmetric blue-shifted line profiles strongly supporting the idea that winds from some Herbig Ae/Be arise in a similar way as winds from CTTSs. Four of these Herbig Ae/Be stars had multi-component profiles. Three of these are examined here using spectro-astrometry, along with R Mon which shows only low velocity emission at the source.

So what new information does spectro-astrometry reveal? In summary the FELs of the four Herbig Ae/Be stars discussed in this chapter behave in a similar way from a spectro-astrometric point of view, to the CTTSs. For the three sources (PV Cep, V645 Cyg and LkH α 233) with multi-component emission, the high velocity emission is displaced further from the source than the low velocity emission. In two cases (PV Cep and V645 Cyg at 24° at N0) I can compare the [OI] λ 6300 line to the [SII] $\lambda\lambda$ 6716,6731 lines and for both sources the [OI] λ 6300 emission is clearly emitted from a position much closer to the driving source than the [SII] $\lambda\lambda$ 6716,6731 emission. Lastly in all cases where I observe the [NII] λ 6583 line it is tracing high velocity emission only. Even though comparing the spectro-astrometric properties of the Herbig Ae/Be stars, to those of CTTSs, is a simple exercise it finally confirms their forbidden emission lines arise in the same manner at least for the earliest stages at least.

Corcoran & Ray (1997) suggest an evolutionary sequence which may account

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for the numerous types of FEL profiles seen in the Herbig Ae/Be stars. They classify their sources into four categories. Category I sources have high and low velocity blue-shifted forbidden emission. Category II sources exhibit low velocity blue-shifted lines only. Category III sources all have low-velocity (narrow) red-shifted FELs and category IV sources have unshifted FELs. The four sources they place in category I (V645 Cyg, PV Cep, LkH α 233 and Z Cma) are all known drivers of molecular outflows. Also category I one stars consist mainly of Hillenbrand Group II sources (Hillenbrand, Strom, Vrba, & Keene, 1992) which are deeply embedded, relatively young intermediate mass stars, analogous to the Class I low mass YSOs (see also section 5.3.3). Hence Category I sources are clearly the least evolved and are placed at the beginning of the evolutionary sequence. Category II stars display signs of being representative of a more evolved state where the conditions for high velocity extended outflows have died away but inner region of disk may still excite a low velocity wind. Corcoran & Ray (1997) argue that at the late stages of evolution the disk becomes optically thin hence both the red-shifted and blue-shifted parts of the jet or disk wind are visible, explaining Category III and IV sources. Alternatively these sources could have completely dispersed their circumstellar disks and are producing their [OI] λ 6300 emission as a spherically symmetric wind.

5.3.2 Outflow Activity in the Vicinity of V645 Cyg

The key to unravelling the outflow activity in the vicinity of V645 Cyg depends on understanding the relationship between the knots N0 and N1. Are there two outflows present driven separately by N0 and N1 or are these two knots simply two representations of the same phenomenon? Here I will outline previous arguments supporting both suggestions and then discuss the further insight into this puzzle gained from a study of the position spectra of the H α and [SII] $\lambda\lambda$ 6716,6731 ELRs at N0 and N1, at four P.A.s, as outlined in section 5.2.3.

An interpretation of the N0 and N1 spectra as light reflected along different lines of sight from a single pre-main sequence object is favoured (Cohen, 1977; Goodrich, 1986b; Hamann & Persson, 1989). Cohen (1977) present spectro-photometric and spectro-polarimetric data on V645 Cyg and conclude that activity in the area of this star can be most easily explained in terms of a bipolar nebula (N0 and N1) whose central star is not seen. He highlights the fact that the spectral similarity between N0 and N1 is strong and that they are both significantly polarised with comparable

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directions of electric vector. It is likely that the true source position is close to N0 (Hamann & Persson, 1989). Indeed the H₂O maser source lies within $\sim 0''.3$ of N0 (Lada et al., 1981).

Corcoran (1995) argues for the presence of two sources and hence two outflows. Firstly the values for the electron densities of the emission features associated with N1 are much lower than those calculated for N0, $1,000 \text{ cm}^{-3}$ as compared to $10,000 \text{ cm}^{-3}$. The absence of the FeI λ 6822 and FeI λ 6593 emission lines present in the spectrum of N0, in that of N1 are also noted. Thirdly he claims that the differences in the velocity structure, that is the differences in velocity of the LVC and HVC of the [SII] $\lambda\lambda$ 6716,6731 lines at P.A. 325° and the fact that the ELRs of N1 are spatially offset towards N0, all mean that N1 is also driving a separate outflow. Corcoran (1995) gives the velocity of the HVCs of N0 and N1 (averaged between the [SII] λ 6716 and [SII] λ 6731 lines) at -440 kms^{-1} and -390 kms^{-1} and the LVCs at -85 kms^{-1} and -100 kms^{-1} respectively.

The above author also analysed the H₂ emission in the region of V645 Cyg and detected some regions of shocked emission, which he labelled objects A to F. In Figure 5.10 I reproduce the image of the H₂ emission presented in the above thesis clearly marking the *approximate* position of objects A to F and the [SII] knot discovered by Hamann & Persson (1989). Corcoran (1995) interprets the pattern of the H₂ knots as further evidence of separate outflows. He notes that objects B, E and F are offset slightly from N1 and hence could be associated with an outflow from this position. Also object A is along the axis connecting N0 to the [SII] knot and its morphology is very similar to a bow shock, making it part of any flow from N0.

The analysis of the optical spectra of N0 and N1 presented here supports the suggestion that they are not separate sources but reflections of an embedded source and outflow close to N0. The following points are critical

1. There are important similarities between knots N0 and N1. The [SII] $\lambda\lambda$ 6716,6731 ELRs at both knots have high and low velocity components at comparable velocities (see section 5.2.3) and the H α line has an outflow component at a similar velocity in all cases. That is at -370 to -380 kms^{-1} at N0 at 0° and 24° and at -420 at N1 at 325° . It is true that the H α blue-shifted outflow component is seen at different P.A.s for both knots but this may attest to the fact that complicated scattering processes are at work around the central em-

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bedded YSO and outflow. Hence knots N0 and N1 are simply reflections along different lines of sight to the source, meaning that different features, such as the secondary peak in the $H\alpha$ blue-wing, become apparent at different P.A.s for both knots.

2. The blue-shifted outflow is strongly seen at N1 at 325° . This position angle agrees with the P.A. of the molecular outflow which is recorded as being orientated in a NW-SE direction (Rodríguez, Torrelles, & Moran, 1981; Torrelles et al., 1987; Schulz et al., 1989; Verdes-Montenegro et al., 1991). The spectro-astrometric plots of the emission ($[SII]\lambda\lambda 6716, 6731$ and $H\alpha$) at N1 at 325° also concur with the direction of the molecular outflow. The blue-shifted molecular lobe is in a south-easterly direction and the blue-shifted emission from N1 at a P.A. of 325° is offset to the south.
3. At all P.A.s the offset in the blue-shifted forbidden and $H\alpha$ emission at N0 is displaced in a direction that is not consistent with the displacement of the blue-shifted emission at N1 or the orientation of the blue-shifted molecular outflow. This is the only important difference between the spectra of N0 and N1. This does not mean that the same outflow is not being observed at N0 and N1. One possible explanation could be that at N0 the emission from star and outflow are reflected from different places hence the offset of the forbidden emission relative to the continuum is not a true representation of their true relative displacement. A similar situation was seen for R Mon in section 5.2.1.

In Figure 5.11 a direction for the true outflow is predicted. It is likely that the outflow is launched by a deeply embedded source lying close to N0. The outflow is orientated close to a P.A. of 325° with the blue-shifted lobe to the SE and the red-shifted lobe to the NW. Hence the spectrum of N1 at 325° is a very close representation of the true outflow and the knots may even be seen directly. While it is clear that there are variations between the spectra of N0 and N1, these discrepancies can easily be explained by concluding that the geometry of the reflections producing N0 and N1 are different, resulting in asymmetrical representations of the same feature.

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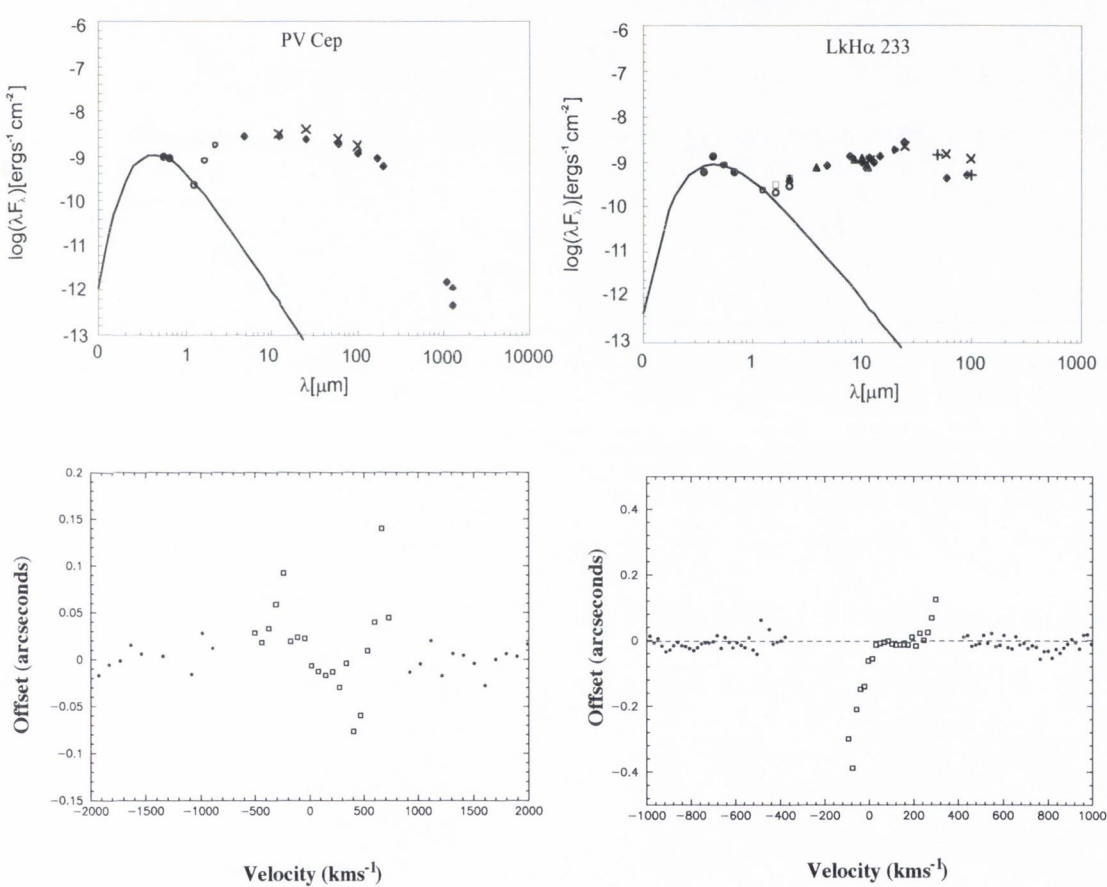


Figure 5.23: Spectro-astrometric plots of the H α ELRs at PV Cep and LkH α 233 and their SEDs. The SEDs are taken from the work of Agueda Gras-Velázquez (Whelan, Gras-Velázquez & Ray, 2005, in preparation).

5.3.3 Circumstellar Disk Dust Holes

As explained in Chapter 4 Section 4.4.1 bipolar displacements in permitted emission lines like $H\alpha$ or $Pa\beta$, where only blue-shifted offsets are measured for the FELRs, can be used to infer the presence of circumstellar disk dust holes (Takami et al., 2001; Takami, Bailey, & Chrysostomou, 2003; Whelan et al., 2004). Essentially there are regions of lowered opacity in the disk close to the source, where extinction is low enough for the permitted lines, which form much closer to the driving source than the FELs, to be detected. One idea is that dust has been cleared by an orbiting protoplanetary object (Steinacker & Henning, 2003; Calvet et al., 2002). Or alternatively the dust grains have started to grow lowering the opacity (Testi, Natta, Shepherd, & Wilner, 2003).

These dust holes are also inferred from the SEDs. The infrared excess observed for the majority of YSOs comes from the circumstellar disk and any lack of infrared excess points to an absence of circumstellar material. To date, not including results presented in this chapter, there are four YSOs (RU Lupi, CS Cha, V536 Aql and LkH α 321) where red-shifted displacements in their permitted ELRs have been taken as a sign of changes in their circumstellar disks. In each case the spectro-astrometric plots of their permitted emission has been compared to their SEDs and for RU Lupi, CS Cha and V536 Aql good agreement is seen. Both the maximum measured offset and the SED can be used to constrain the size of the dust hole or the extent of the region in the disk over which the changes are occurring. If using the maximum offset in a particular permitted line as a measure of the projected radius of the hole it is important to note that the apparent hole size will increase with the wavelength of the lines being studied, as the transparency of the disk will be greater at longer wavelengths. For example spectro-astrometric observations of V536 Aql at $Pa\beta$ and $H\alpha$ gave the size of the dust hole in the disk of this YSO at 16.5 AU and 7 AU for $Pa\beta$ and $H\alpha$ respectively.

As outlined in section 5.2 PV Cep and LkH α 233 show red-shifted offsets in their $H\alpha$ ELRs, at velocities where one would expect to see the counter-flow. Here I shall use the spectro-astrometric plots of both sources to estimate the projected radius of the dust holes as derived from the measured offsets. These values in turn shall be used to predict where the dip in the excess should appear in the SED and I shall examine whether such dips are present. I shall use the same techniques as outlined for the CTTS V536 Aql in Chapter 4. The SEDs are shown in Figure

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5.23 and again are taken from the work of Agueda Gras-Velázquez, (Whelan, Gras-Velázquez & Ray, 2005, in preparation).

For PV Cep infrared and sub-millimeter photometric measurements from Abraham et al. (2000) (and references within) are represented by full diamonds and the IRAS points are the crosses (Weaver & Jones, 1992). The empty circles represent the near-infrared points taken from the 2MASS and lastly the filled circles are the V, R and I band points (Neckel & Staude, 1984; de La Reza et al., 1986; Blanco, 1962). For LkH α 233 the full diamonds, crosses and empty circles are again the infrared, sub-millimetre and IRAS points, taken from Abraham et al. (2000) and Weaver & Jones (1992) and the measurements in the J, H and K bands from the 2Mass, respectively. Further near-infrared photometric results were taken from Allen (1973) (open squares) and Berrilli, Lorenzetti, Saraceno, & Strafella (1987) (triangles). U, B, V and R band photometry from Herbst & Shevchenko (1999) and photometry at 50 μ m and 100 μ m (Evans, Levreault, & Harvey, 1986) are marked on the SED by full circles and daggers respectively.

PV Cep is located at a distance of 500 pc. The H α red-wing is displaced out to $\sim 0''.06$, which equals ~ 29 AU at 500 pc. The displacement in the red-wing infers that the outflow in H α can be observed up to 30 AU from the source before it is obscured. The luminosity and spectral type of PV Cep are given at 100 $L_{\odot}$ and F2 (6700K) (Mundt & Ray, 1994; Corcoran & Ray, 1998b). Using equation 4.3 I obtain a value of 7.5 $R_{\odot}$ for $R_{\star}$ and inputting this value into equation 4.2 I estimate a range of values of $T(r)$ (depending on the value of q used, refer to Chapter 4 section 4.3.4), 30 K to 310 K. These temperatures correspond to a wavelength range of 100 μ m to 9.3 μ m. In Figure 5.23 the SED of PV Cep has no striking lack of excess but there is some lack of emission at $\sim 1\mu$ m.

The distance, luminosity and spectral type of LkH α 233 are given at 880 pc, 121 $L_{\odot}$ and A5 (8260K) respectively (McGroarty et al., 2004a; Corcoran & Ray, 1998b). Hence $R_{\star}$ equals 5.37 $R_{\odot}$. The red-shifted displacement in the H α line can be taken at $\sim 0''.1$. This offset equals a gap radius of ~ 86 AU. There is a lack of emission in the SED of LkH α 233 between approximately 1 μ m and 10 μ m (2900K to 290K). This equals 1 AU to 40 AU for values of the constant q between 0.75 and 0.4 (see again Chapter 4 section 4.3.4).

Both sets of results derived above, suggest a poor agreement between how the SEDs of these sources and the measured red-shifted offsets in the H α emission constrain the size of any dust hole that may be present in their disks, especially for

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PV Cep. It is important to address here the validity of applying equation 4.1 to the disk of a Herbig Ae/Be star. The power-law radial temperature dependence $T(r) \propto r^{-q}$ of circumstellar material as described by Beckwith & Sargent (1993) assumes that all circumstellar material is confined to a spatially thin passive disk (for $0.5 \leq q \leq 0.75$). The majority of the studies of circumstellar disks focus on the TTSSs. However as mentioned previously Hillenbrand, Strom, Vrba, & Keene (1992) carried out a massive study of the accretion disks of Herbig Ae/Be stars. They analysed the excess emission in the infrared SEDs of 47 sources and accordingly classified them into three groups. Group I objects were defined as the intermediate mass counterparts to the CTTSs in that their SEDs were well fitted by assuming that the excess arose in flat spatially thin circumstellar disk as done for the CTTSs. Group II objects are characterised by a flat or rising infrared spectrum and it was proposed that these objects are deeply embedded and surrounded by an envelope of infalling gas and dust, rather than a flat disk. Lastly Group III objects have weak infrared excesses and were assumed to be diskless. The above authors also mention that the SEDs of many of their sources show a lack of excess between $1\mu\text{m}$ to $2\mu\text{m}$ (similar to PV Cep) which signals the existence of an optically thin region (dust hole) within the inner few stellar radii of the disk. LkH α 233 is categorised in the above study as a Group II object therefore the radial temperature dependence adopted for the above calculations for $0.5 \leq q \leq 0.75$, is not applicable to the disk of this source.

The inclination of the disks of both sources with respect to the line of sight should also be considered (see Chapter 4 section 4.3.4). The two components that make up the FELs of PV Cep are well separated hence a reasonable first estimate for I for PV Cep is 45° . This estimate increases the dust hole size from 29AU to 41AU. For LkH α 233 it is more difficult to estimate the jet inclination angle, from just the FEL profile. No obvious separation between high and low velocity emission is observed, yet the velocity of the jet is not high enough to suggest that the jet is inclined perpendicular to the plane of the sky.

To summarise the red-shifted offsets in the H α ELRs of PV Cep and LkH α 233 indicate the presence of a circumstellar dust hole in the disks of these sources. The value of the maximum displacement can be used to constrain the maximum extent of these holes/gaps. The presence of these regions of lowered opacity should result in a lack of excess emission in the SEDs of these two Herbig Ae/Be stars and assuming a radial temperature dependence for the disks I can calculate using

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the estimated values for the gap radii, where this dip in the excess emission should be seen i.e. at what wavelength. In both cases there is some lack of excess in the SEDs however where this occurs does not agree with the prediction made using the measured displacements. The radial temperature dependence used to calculate the wavelength at this radius cannot necessarily be used for Herbig Ae/Be stars as it assumes that circumstellar material is confined to a flat passive disk. If the disks of PV Cep and LkH α 233 are active rather than passive any dust hole would not be obvious from their SEDs. A much better agreement is seen for V536 Aql in Chapter 4.

Conclusion

The technique of spectro-astrometry has proved a vital tool for studying outflow activity at the base of T Tauri outflows. In particular it was used to provide observational evidence supporting the disk-wind model of Kwan (1997). Spectro-astrometry has been used by me in preceding chapters to provide spatial information on ELRs closer to the driving sources of outflows than has been previously possible and to study dust holes in the disks of some CTTs. While much emphasis has been placed on a comparison between the CTTs and the Herbig Ae/Be stars this is the one of the first uses of spectro-astrometry to probe the FELRs of these YSOs in the same manner as has been done by me and others for the CTTs. To make this comparison was the main aim of the work I detail in this chapter. As a result of the observations I discuss here I can make an overall comparison between the CTTs and the Herbig Ae/Be stars however I also reveal some new information about the individual sources. I make the following conclusions.

1. On the basis of the spectro-astrometric results I present I conclude that activity in the jet launching region of the Herbig Ae/Be stars parallels what is known for the CTTs. It is clear that the disk-wind model can also be used to explain the FELRs of the sources in my admittedly very small sample. High velocity emission in all cases is displaced to a greater extent than the low velocity emission and the changes in density and temperature with increasing distance from the star are mirrored in the offsets of the different lines. Generally [SII] $\lambda\lambda$ 6716,6731 and [NII] λ 6583 are displaced further than the [OI] $\lambda\lambda$ 6300,6363 emission lines.

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2. For PV Cep and LkH α 233 I detect red-shifted offsets in the H α ELR where only blue-shifted emission is seen in the FELs. Hence this is a similar situation to what is described for V536 Aql and LkH α 321 in Chapter 4, where evidence for the presence of gaps or dust holes in the disks of these two Herbig Ae/Be stars is presented. Essentially the red-shifted outflow is being seen through the gaps in the disks. The FELs are formed much further out (15 AU compared to 150 AU, at 150 pc) so the red-shifted forbidden emission still remains obscured by the disk. As in Chapter 4 I constrain the radii of these dust holes from the maximum offsets and compare my estimates to their SEDs. While in Chapter 4 there is a good agreement between the SED and position spectrum of V536 Aql it appears that for the Herbig Ae/Be stars the measured offsets, do not concur with the location of any dust holes as estimated from the SEDs.
3. Spectro-astrometric measurements also illustrate the effects of scattering. This is very common in the vicinity of intermediate mass sources as they are often embedded in a large amount of circumstellar material. In R Mon the source is seen in scattered light but the forbidden emission in the outflow is seen directly. In the case of V645 Cyg a study of the spatial properties of the two knots present close to the source position allowed the question regarding the true nature of these knots to be further addressed. Results presented support that idea that N0 and N1 are simply different images of the same outflow. It is suggested that the outflow launched closer to N0 than N1, is orientated in a NE-SW direction (blue-shifted to the south). Complicated scattering effects may explain the different orientation of the outflow at N0.

In summary the evidence suggests that outflow activity from Herbig Ae/Be stars is a scaled-up version of what occurs in TTSs.

Chapter 6

Studying Outflow Activity in Brown Dwarfs

Introduction

The study of very young BDs in star forming regions has a special importance, as clearly the first question that must be asked about these objects is, how are they formed? More and more BDs are now being discovered and analysed in nearby stellar nurseries such as Taurus (Briceño, Hartmann, Stauffer, & Martín, 1998; ?), ρ -Ophiuchi (Wilking, Greene, & Meyer, 1999) or Orion (Lucas & Roche, 2000). Understanding the formation of BDs can only increase our limited knowledge of the processes active in star forming regions and indeed allow the universality of these processes at the lower end of the mass spectrum to be addressed.

For example, it has been suggested that BD formation is initiated in a similar manner to low mass stars, i.e. through the slow contraction of a molecular cloud core (Shu, Adams, & Lizano, 1987). Either BDs form from smaller cores than low mass stars, or else the growth of a stellar mass core is halted by its ejection from the molecular cloud (Reipurth & Bally, 2001; Kroupa & Bouvier, 2003). As well as the “ejected embryo” scenario it is also possible that BDs begin in circumbinary disks and are then removed through dynamical interaction with the central binary stars (Jiang, Laughlin, & Lin, 2004). Indeed BDs may have more than one formation mechanism, but in any event it is reasonable to compare them with low mass YSOs, in particular the CTTSs. Specifically, do BDs undergo accretion and have accretion disks, and if they are accreting material do they drive outflows? In this chapter the

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possibility of detecting outflows from BDs is addressed.

Certainly evidence for accretion in sub-stellar objects exists. The presence of disks has been confirmed from a study of the SEDs of a number of BD candidates (Natta et al., 2002; Pascucci, Apai, Henning, & Dullemond, 2003) and high resolution optical spectra point to the existence of a T-Tauri like accretion phase for BDs (Jayawardhana, Mohanty, & Basri, 2003). To date any hint that outflows may also be a feature of very low mass sources has only come from the detection of optical FELs in their spectra (Fernández & Comerón, 2001; Muzerolle et al., 2003; Natta et al., 2004). As mentioned in Chapter 1 it is likely that any outflow driven by a BD would be difficult to detect (Masciadri & Raga, 2004). Indeed it has not yet been possible, even with the worlds biggest and most powerful telescopes to image a sub-stellar flow.

As is strongly evident from numerous studies and the work discussed so far in this thesis, FELs trace outflow activity and when used in combination with the technique of spectro-astrometry, are a very powerful tool for exploring outflows on very small spatial scales. Hence, in theory, using this technique to measure any displacement in the FELs found in the spectra of BDs is an ideal method for resolving their outflows. Here the optical FEL spectra of two BDs (see Table 6.1) are analysed. I look closely at the velocities of their FELs, compare the spectra to FEL spectra of CTTSs and most interestingly, apply the technique of spectro-astrometry to measure the offset of the FELs in the spectrum of ρ -Oph 102, revealing for the first time the presence of an outflow.

6.1 Observations

High resolution optical echelle spectra of ρ -Oph 102 and LS-RCrA 1 are presented here. Both sets of data have been discussed previously in separate studies (Natta et al., 2004; Barrado y Navascués, Mohanty, & Jayawardhana, 2004) but were kindly provided so that the displacement of the FELRs could be studied. I wish to thank F. Bacciotti, A. Natta and L. Testi (Arcetri Observatory Florence) for allowing me to work on the echelle spectrum of ρ -Oph 102 and R. Jayawardhana (University of Toronto) and S. Mohanty (Center for Astrophysics Harvard) who provided the spectrum of LS-RCrA 1.

Observations of ρ -Oph 102 were taken with the VLT in May 2003 using the UV-

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ρ -Oph 102		
RA (J2000)	16 27 06.5	
Dec (J2000)	-24 41 47.1	
T_{eff} (K)	2700	
Age (Myr)	<1	
Mass ($M_{\odot}$)	~ 0.06	
Accretion rate ($M_{\odot}yr^{-1}$)	1.25×10^{-9}	
LS-RCrA 1		
RA (J2000)	19 01 46.8	
Dec (J2000)	-37 00 12.1	
T_{eff} (K)	2700 ± 100	
Age (Myr)	~ 8	
Mass ($M_{\odot}$)	~ 0.035	
Accretion rate ($M_{\odot}yr^{-1}$)	$10^{-9}-10^{-10}$	

Table 6.1: Table listing the positions and some of the basic properties of ρ -Oph 102 and LS-RCrA 1. Accretion rates were derived using the Ha emission line and are taken from Natta et al. (2004) for ρ -Oph 102 and from Barrado y Navascués, Mohanty, & Jayawardhana (2004) for LS-RCrA 1.

Visual Echelle Spectrograph (UVES). Observations of LS-RCrA 1 were also taken in May 2003 but this time with the Magellan Inamori Kyocera Echelle (MIKE) spectrograph on the Magellan Baade telescope. In both cases only the red part of the spectrum was analysed and the pixel scale and spectral resolution were $0''.182$, $R=40,000$ and $0''.13$, $R=19,000$ for ρ -Oph 102 and LS-RCrA 1 respectively. The initial reduction and velocity calibration of this data was carried out using standard IRAF routines. The absolute velocity calibration was checked by self-calibrating the arc spectra. Overall variations were only of the order of 1 kms^{-1} .

6.2 Spectro-astrometric Analysis

To date spectro-astrometry has mainly been used to study outflows from low mass sources, and young binaries, as discussed in Chapter 2. The application of this technique to the spectrum of a BD posed new challenges. Firstly their optical continuum emission in the red is very weak in comparison to that of a typical CTTS. This is partly due to their much smaller radii ($< 0.5R_{\odot}$, refer to Mohanty et al 2004) and hence surface area, but also because emission from a BD will peak

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in the near-infrared. In the optical one is looking at the low intensity part of a BD spectrum. Secondly the predicted angular displacement in the FELR of a BD spectrum is 3-10 times less than what is seen again for a typical CTTs at the same distance (see section 6.4.1). As a result the scatter in the continuum position drowns the offset in the ELR. This is illustrated in Figure 6.1.

Looking at the ρ -Oph 102 [OI] λ 6300 ELR the number of counts, N_c is significantly less at the continuum than at the line. N_c average for the continuum is ~ 10 compared to ~ 60 for the [OI] λ 6300 line peak. Hence the spectro-astrometric plot just appears as a scatter with a tightening in the scatter at the line. It is impossible to tell if there is any real displacement in the [OI] λ 6300 line. The same is true of the H α ELR. The opposite case applies to the [OI] λ 6300 emission from DG Tau. N_c average for the continuum is ~ 1500 compared to ~ 770 for the [OI] λ 6300 line peak. For both the continuum and line N_c is large enough for a very accurate spectro-astrometric signature to be obtained and the scatter in the continuum emission is very tight around zero with the [OI] λ 6300,6363 lines clearly displaced. It is also important to note here that the velocity resolution of the ρ -Oph 102 spectrum is greater than that of the DG Tau spectrum due to over-sampling (1 km s^{-1} and compared to 10 km s^{-1} for DG Tau). This also decreases the signal to noise of the ρ -Oph 102 spectrum.

In general the spectro-astrometric accuracy can be increased by binning the emission so that each extracted spatial profile is the sum of two or three adjacent profiles. A usable spectro-astrometric signature was extracted from the spectrum of ρ -Oph 102 by binning the continuum and ELRs separately and in such a way as to ensure that a comparable amount of photons were sampled at each point or that the average S/N was the same. For example, for the [OI] λ 6300 ELR the continuum emission was sampled using a bin of 12 columns and the ELR using a bin of 2 columns. As the [OI] λ 6363 line is approximately 3.5 times weaker than the [OI] λ 6300,6363 line, I increased the bin to 7 columns for the [OI] λ 6363 ELR, while I still binned the continuum over 12 columns. The errors in the position of the continuum are therefore similar to the errors in the position of the emission line. The $\pm 1\sigma$ error is represented by a dashed line in each of the spectro-astrometric plots.

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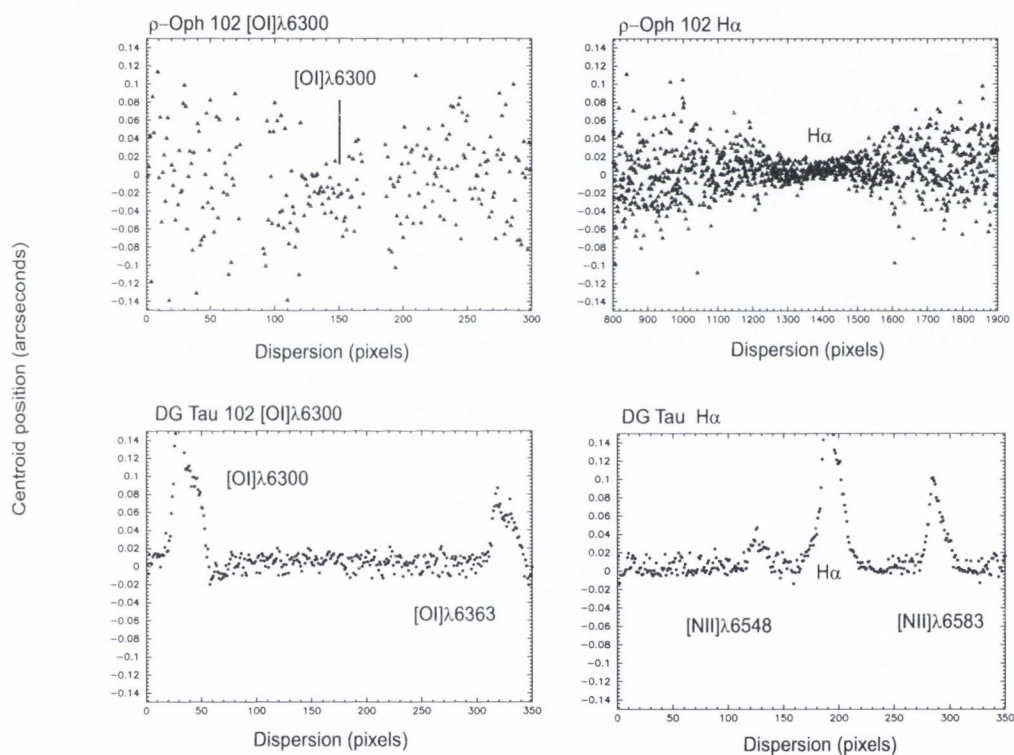


Figure 6.1: Spectro-astrometric plots highlighting the weakness of the ρ -Oph 102 continuum as compared to the continuum of DG Tau, a typical CTTS. The position of the line and continuum is measured in each case by fitting a gaussian to the PSF at each column. The continuum was not subtracted so the displacement seen in the FELs of DG Tau is actually larger.

6.3 Results

Results are presented in the form of emission line profiles giving the systemic velocities of the FELs and the $H\alpha$ line present in the spectra of both sources and spectro-astrometric plots (Figures 6.2 to 6.5). The systemic velocity of ρ -Oph 102 was measured from the $\text{Li}\lambda 6708$ absorption line to be $\sim +7 \text{ kms}^{-1}$ with respect to the LSR, and for LS-RCrA 1 the value is given at $+5 \text{ kms}^{-1}$ (Hartigan & Graham, 1987).

6.3.1 ρ -Oph 102

The nearby ρ -Ophiuchi cloud ($d=140\pm 10 \text{ pc}$) is an excellent example of a stellar nursery. This region has been the subject of many surveys to date and it was as part of a near-infrared survey by Greene & Young (1992) that the BD ρ -Oph 102 was first detected. It was also included in an ISOCAM study of the ρ -Ophiuchi cloud by Bontemps et al. (2001). Several properties of this BD including its mass and accretion rate as measured by Natta et al. (2004) are listed in Table 6.1. It was also noted by the above authors that the optical spectrum of ρ -Oph 102 contains a number of FELs, suggesting mass outflow.

The $[\text{OI}]\lambda\lambda 6300, 6363$, $[\text{NII}]\lambda 6583$ and $[\text{SII}]\lambda\lambda 6716, 6731$ lines are all present. The systemic velocities of these lines are listed in Table 6.2, the equivalent widths in Table 6.3 and the emission line profiles are shown in Figures 6.2, 6.3 and 6.4. The average velocity of the FELs is $\sim -41 \text{ kms}^{-1}$ which is suggestive of the presence of an outflow. Moreover the blue-shifted asymmetry mirrors what is seen in CTTSs, and points to the presence of a disk. A second indication that an outflow is present comes from the $H\alpha$ line. Its profile is clearly asymmetrical, i.e. the blue-shifted wing of the line appears to be absorbed in a P-Cygni like fashion at a similar velocity to the FELs ($\sim -80 \text{ kms}^{-1}$). However a classical P-Cygni profile, i.e one that dips below the continuum, is not observed but such a profile is, in any event, a rare occurrence even amongst the CTTSs.

Of the five FELs detected only the $[\text{OI}]\lambda\lambda 6300, 6363$ and $[\text{SII}]\lambda 6731$ lines were strong enough for any displacement measurements. The weakness of the $[\text{NII}]\lambda 6583$ line, for example, is clear from Figure 6.4. In Figure 6.2 the emission line profiles of the $[\text{OI}]\lambda\lambda 6300, 6363$ lines and the corresponding spectro-astrometric plots are shown. A clear offset in the $[\text{OI}]\lambda\lambda 6300, 6363$ lines is observed. Measurements for

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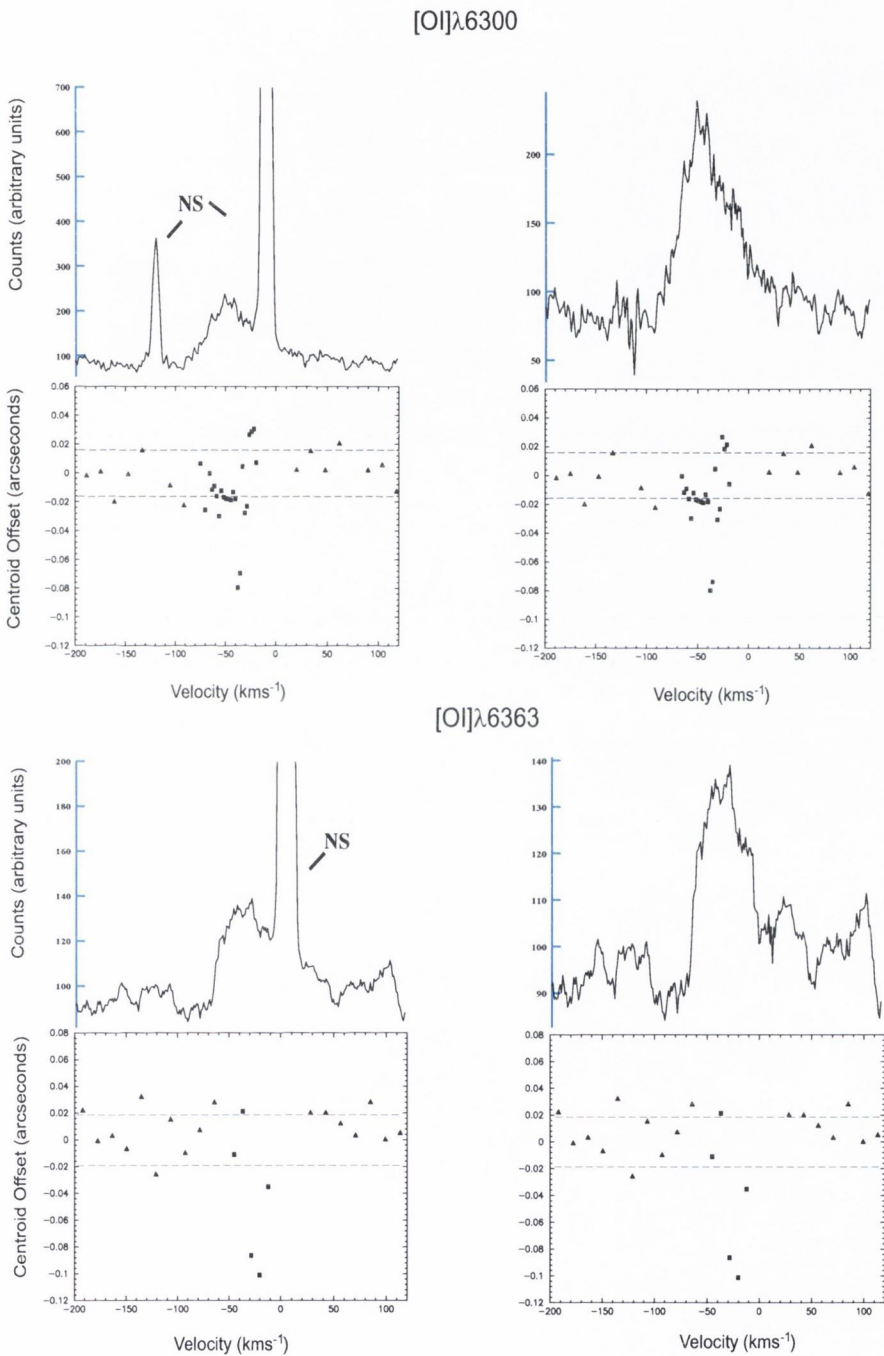


Figure 6.2: Forbidden emission line regions of ρ -Oph 102: The [OI] $\lambda\lambda$ 6300,6363 emission line regions were initially fitted with the night sky (NS) lines still present (left panel). However in order to check for any contribution from the night sky lines to the measured displacement I removed the lines in the same manner as I did the continuum subtraction and then fitted the same points (right panel). There was *no difference* in the offset of the [OI] $\lambda\lambda$ 6300,6363 emission line regions. Note the NS regions were excluded. All velocities are systemic.

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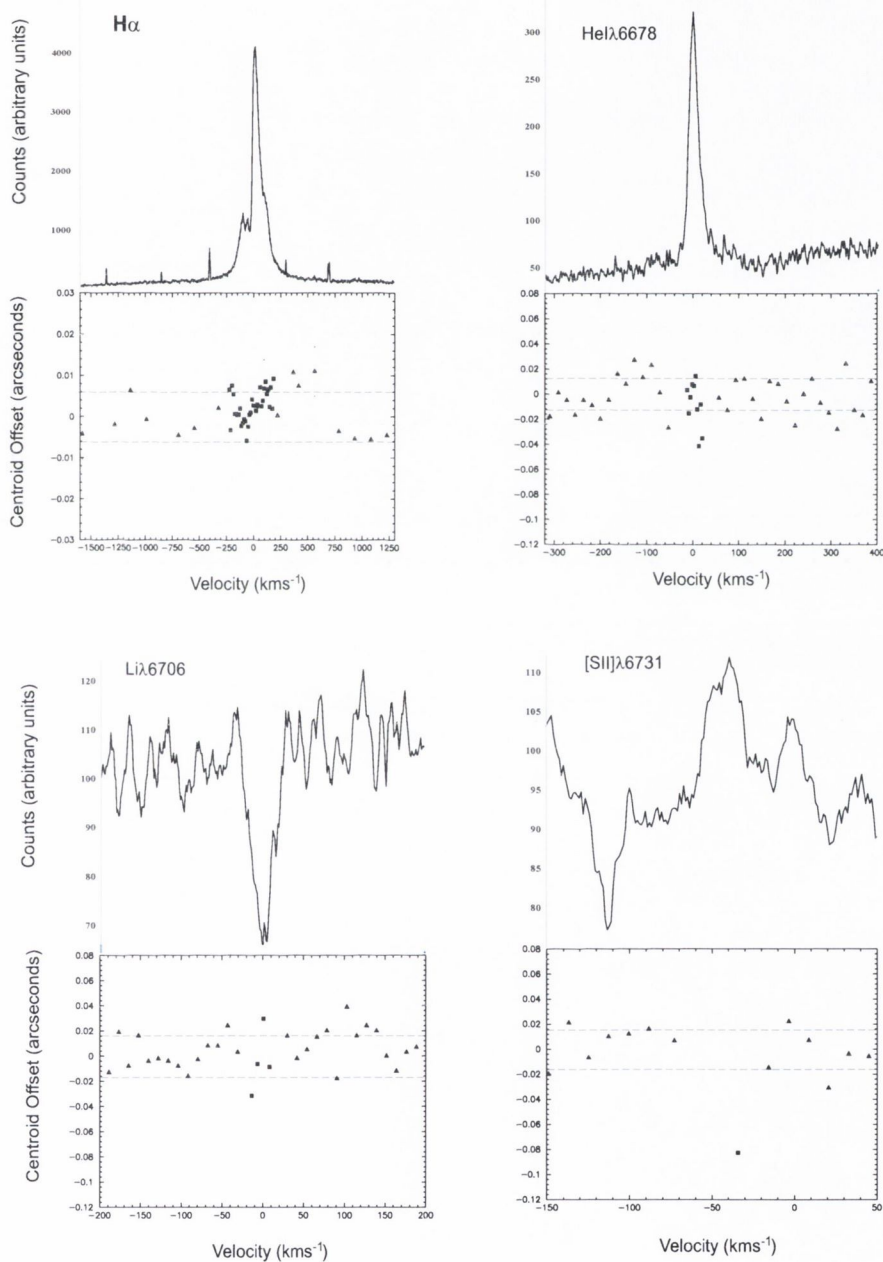


Figure 6.3: Other lines present in the spectrum of ρ -Oph 102, included H α , He I λ 6678, Li λ 6706 and [SII] λ 6731. For all of these lines it was possible to measure the displacement of the line with respect to the continuum. The displacement in the [SII] λ 6731 line is comparable to that observed for the [OI] $\lambda\lambda$ 6300,6363 doublet as expected. For the other emission lines, and the Li absorption line, no offset is detected.

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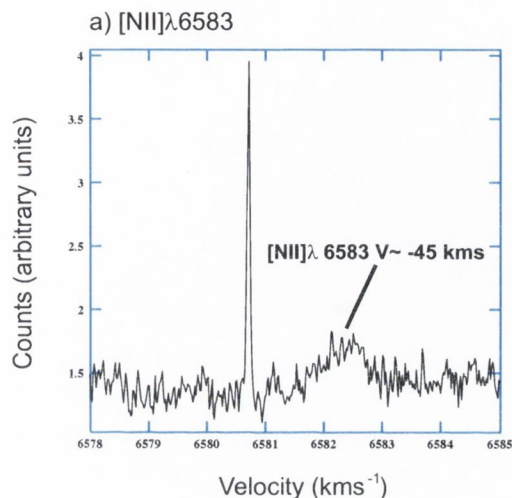


Figure 6.4: Line profile of the $[\text{NII}]\lambda 6583$ emission from ρ -Oph 102. An estimate of the peak systemic velocity is given.

both lines were made before and after night sky line subtraction. In the vicinity of the $[\text{OI}]\lambda\lambda 6300, 6363$ lines, there were in fact several night-sky lines. For example adjacent to the $[\text{OI}]\lambda 6300$ line a very weak OH line, at around -122 km s^{-1} as well as the strong, but narrow, $[\text{OI}]\lambda 6300$ line at approximately -9 km s^{-1} are observed. Neither the continuum nor the $[\text{OI}]\lambda\lambda 6300, 6363$ emission was fitted in the region of any night-sky lines, explaining the gaps in the continuum data points in Figure 6.2. Note that the offsets plotted in all figures are measured with these night-sky lines still present. However, if the night-sky lines are removed, and the displacement measured as before, no differences in the plotted offsets are seen. This is not surprising given the narrow width, and position with respect to the BD emission, of the night-sky lines. The night-sky line subtraction was done in a similar way to the continuum subtraction using the IRAF continuum task.

Figure 6.3 presents the spectro-astrometric plots and emission line profiles of some other lines of interest in the spectrum. In particular note that a displacement in the $[\text{SII}]\lambda 6731$ ELR is recorded at a similar velocity and offset to the $[\text{OI}]\lambda\lambda 6300, 6363$ lines. Overall the centroids of all the measurable forbidden lines in the spectrum of ρ -Oph 102 are displaced to the south, i.e. have negative offsets with respect to the continuum and these offsets reach a maximum of $0''.08$ - $0''.1$ at a blue-shifted velocity of $\sim -41 \text{ km s}^{-1}$. The scale of this blue-shifted offset would suggest a minimum (projected) disk radius of $0''.1$ ($\geq 15 \text{ AU}$ at the distance of the ρ -Ophiuchi cloud) in order to hide any red-shifted component. There is no clear

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Object	Emission Line	V(kms ⁻¹)
ρ -Oph 102	[OI] λ 6300	-40 $\pm$ 6
	[OI] λ 6363	-38 $\pm$ 6
	[NII] λ 6583	-45 $\pm$ 5
	[SII] λ 6731	-45 $\pm$ 5
LS-RCrA 1	[OI] λ 6300	-9 $\pm$ 4
	[OI] λ 6363	-7 $\pm$ 5
	[NII] λ 6583	-19 $\pm$ 4
	[SII] λ 6717	-12 $\pm$ 5
	[SII] λ 6731	-15 $\pm$ 4

Table 6.2: Table showing the peak systemic velocities of the FELs found in the spectra of ρ -Oph 102 and LS-RCrA 1.

spatial offset in H α even though its higher signal to noise potentially would allow one to measure even smaller offsets than observed in the forbidden lines. This is in agreement with the idea that most of the H α emission arises from accretion on much smaller scales than are being probed here (Natta et al., 2004). It is also worth pointing out that if, as is almost certainly the case, the blue ward dip in the H α profile is caused by P Cygni-like absorption from an outflowing wind in front of the star, no offset should be expected. Lastly, no offset is expected in the Li λ 6708 and HeI λ 6678 lines as they are photospheric and chromospheric respectively, and none is found.

6.3.2 LS-RCrA 1

LS-RCrA 1, located in the R Coronae Australis star forming region, was first identified as a BD by Fernández & Comerón (2001). Barrado y Navascués, Mohanty, & Jayawardhana (2004) originally analysed the high resolution spectrum that I discuss here, along with low and medium resolution spectra and gave values for the T_{eff} , age, mass and mass accretion rate of this source, as listed in Table 6.1. One interesting feature of this source as discussed by the above authors is that it appears to be sub-luminous or older, compared to other members of this star forming region. The sub-luminous nature of LS-RCrA 1 is reflected in the weakness of the continuum in the optical spectrum. The cold nature of a BD means that the strength of its continuum emission peaks in the near-infrared (at $\sim 1\mu\text{m}$ for $T_{eff} = 2700\text{K}$) and is much weaker at optical wavelengths. In the optical echelle spectra of BDs, there is a notable decrease in the strength of the continuum emission as

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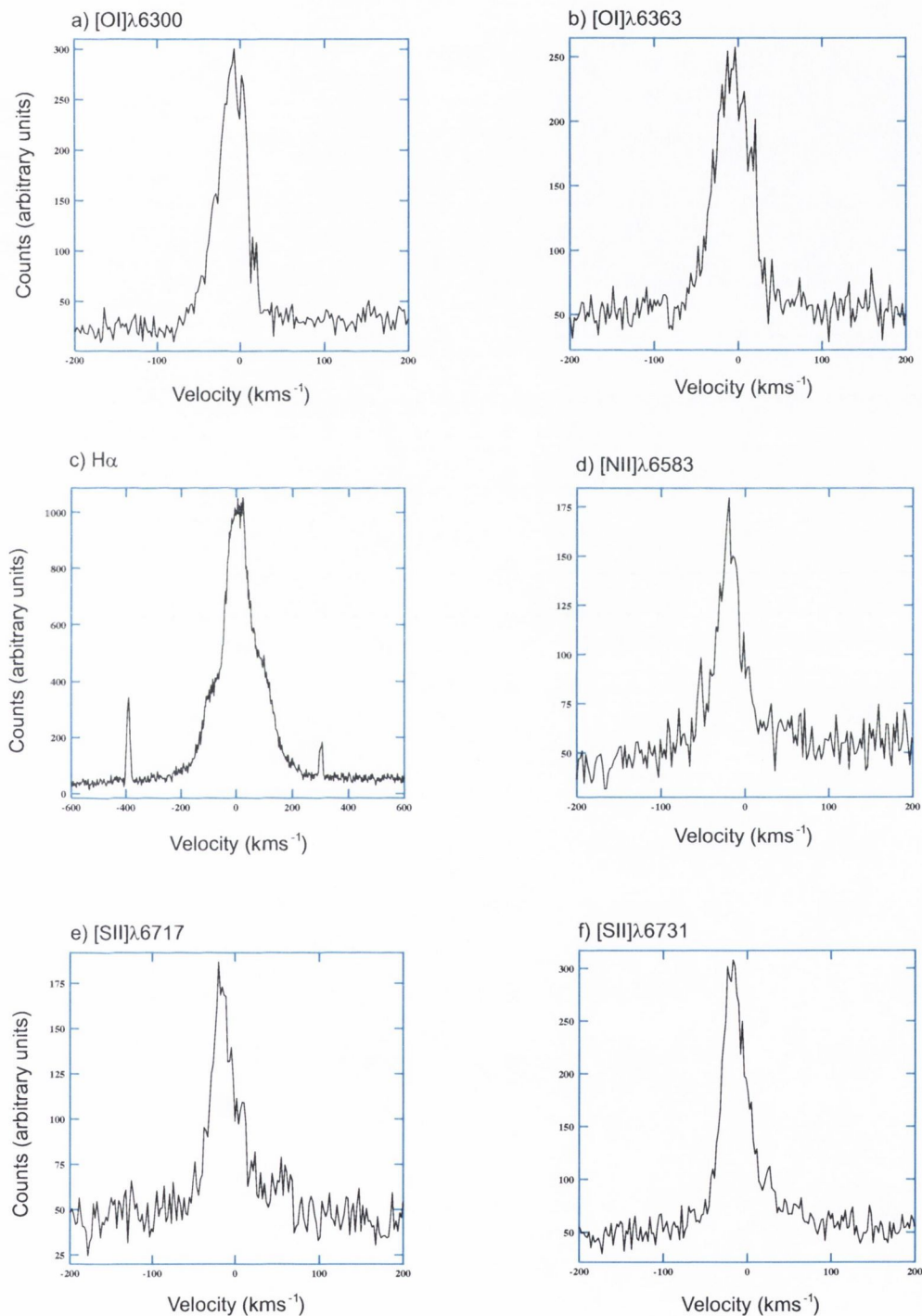


Figure 6.5: Line profiles of the FELs present in the spectrum of LS-RCrA 1. All velocities are with respect to the systemic velocity of the source. The continuum has not been removed and each 1D spectrum is a sum of 6 adjacent rows taken from the centre of the continuum. In the case of the [OI]λλ6300,6363 lines the strong night sky lines are removed from the profiles but two night sky lines are seen either side of the Hα line.

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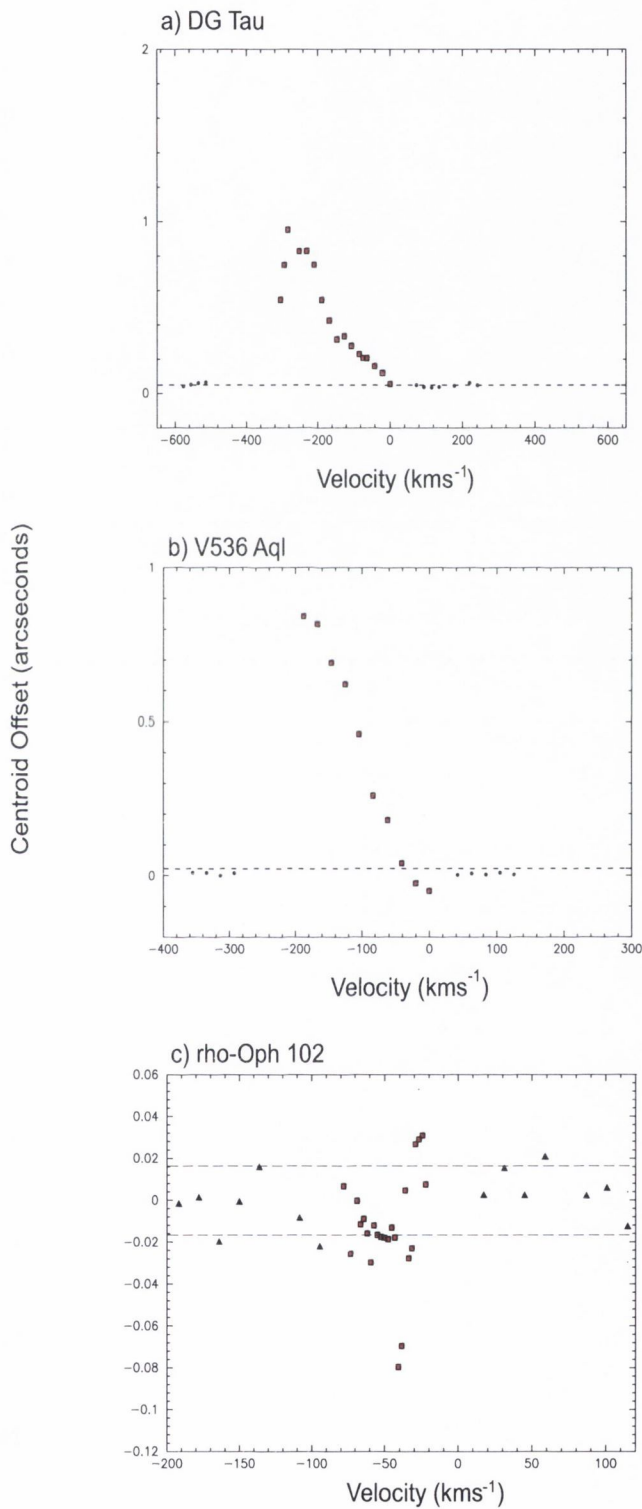


Figure 6.6: Figure comparing the displacement of the [OI] λ 6300 ELR in two CTTSs, DG Tau and V536 Aql and the BD ρ -Oph 102

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we move from the longer to shorter wavelengths, for example from the region of the $\text{HeI}\lambda 6678$ line to that of the $[\text{OI}]\lambda\lambda 6300, 6363$ lines. In this source around the $[\text{OI}]\lambda\lambda 6300, 6363$ lines the continuum was barely detectable. It has been proposed that this source is surrounded by an edge-on disk. This would not only explain its sub-luminous nature but other features, such as strong forbidden lines combined with low accretion rates, the relatively broad wings seen in the $\text{H}\alpha$ line and the lack of any NIR excess (Fernández & Comerón, 2001; Barrado y Navascués, Mohanty, & Jayawardhana, 2004).

As stated the spectrum contains strong FELs. The $[\text{OI}]\lambda\lambda 6300, 6363$, $[\text{NII}]\lambda 6583$ and $[\text{SII}]\lambda\lambda 6716, 6731$ lines are all present and the velocities at which these lines peak are given in Table 6.2. The lines are all blue-shifted again pointing to the presence of a disk but the velocity average for the FELs is only about -10 km s^{-1} , which is lower than that seen in ρ -Oph 102. Such a low velocity however is *consistent* with the fact that we are looking at this system edge-on. The $\text{H}\alpha$ line is also interesting as there is some very slight evidence for a P-Cygni absorption feature in the blue-wing, similar to what is seen for ρ -Oph 102. Figure 6.5 presents the emission line profiles of all the FELs and the $\text{H}\alpha$ line.

Even though the FELs are much more intense than those in the spectrum of ρ -Oph 102 it was almost impossible to measure any displacement in the FELRs. The weakness of the continuum meant that it was very difficult to measure the position of the source i.e. the centre of the continuum. Hence there was no fixed point from which to measure any offset. Also note that the cross dispersion for this spectrum appears to be very low meaning that there was still some slight overlapping between orders. The number of pixels between adjacent orders was small hence the gaussian profiles of the continuum in a particular order did not have large wings and were sometimes incomplete. Overall this spectrum was not at all ideal for the use of spectro-astrometry.

6.4 Discussion

6.4.1 Are we Dealing with a Scaled Down Version of Outflows from CTTSs?

Most of what is now known about FELRs and their relation to the outflow phenomenon comes from the study of the CTTSs (Hirth, Mundt, & Solf, 1997; Davis

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et al., 2003). Hence a comparison between the FELRs of CTTS and the recently discovered FELRs of BDs is an obvious next step. Results presented in Chapter 5 show that for the intermediate mass Herbig Ae/Be stars, the properties of their FELRs i.e. velocity and displacement are simply scaled-up from the properties of the FELRs of CTTSs. For BDs it seems that when it comes to outflow activity, we are dealing with a scaled-down version of CTT flows, as I shall now explain.

The most notable features of the FELRs of CTTSs is that they are mostly blue-shifted and they are often multi-component. It is well documented that the circumstellar disks now known to exist around young stars obscure the receding part of the flow explaining the blue-shifted nature of the forbidden emission (Edwards et al., 1993). As discussed time and time again throughout this thesis the high and low velocity emission components reflect the dual nature of the CTT flows close to their sources. Just considering results discussed in this thesis the HVC and LVC are typically seen at velocities of $\leq 250 \text{ kms}^{-1}$ and $\leq 50 \text{ kms}^{-1}$ respectively. For ρ -Oph 102 and LS-RCrA 1 only one component is seen.

The only information that could be extracted on the spatial properties of the FELRs comes from the [OI] $\lambda\lambda 6300, 6363$ and [SII] $\lambda 6731$ lines in the spectrum of ρ -Oph 102. Overall, displacement averages $\sim 80 \text{ mas}$ at a velocity of $\sim -40 \text{ kms}^{-1}$. This is in line with the prediction that a collimated outflow from a BD is expected to reach the critical density for forbidden emission i.e. $n_e \sim 10^6 \text{ cm}^{-3}$, much closer to the source than a CTTS. This prediction is made by considering how the critical density for a forbidden line is expected to scale with the mass flux through the jet, $\dot{M}_{jet}$, for a BD. Now $\dot{M}_{jet}$ is given by

$$\dot{M}_{jet} = \pi r^2 \rho V_{jet} \quad (6.1)$$

where r , ρ and V_{jet} are the jet radius, density and velocity respectively. The radius in turn is related to the jet opening angle θ (in radians) by $\theta \approx r/L$ where L is the distance to the source along the jet axis and thus

$$\dot{M}_{jet} \approx \pi \rho V_{jet} \theta^2 L^2 \quad (6.2)$$

The escape velocity and hence the jet velocity, for a brown dwarf and a T Tauri star should be approximately the same (Masciadri & Raga, 2004). Moreover the opening angle of such jets seem to be close to their ballistic values, i.e. $\theta \approx 1/\mathcal{M}_{jet}$ where

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$\mathcal{M}_{jet}$ is the jet Mach number. Since the gas temperature determines the sound speed, and this in turn depends on the type of line emission, the Mach numbers for jets from T Tauri stars and BDs are expected to be close. Thus their opening angles should also be similar. Finally the spatial offset observed between the source and the centroid of emission for a forbidden line roughly coincides with the point at which the critical density for a line is reached. From the last equation this offset is expected to scale with $\dot{M}_{jet}^{0.5}$. As mass loss rates from BDs are anticipated to be 2 orders of magnitude lower than the mass loss rates from CTTSs, typical spatial offsets are thus estimated to be 3-10 times smaller. Figure 6.6 is a comparison between the [OI] λ 6300 emission from two CTTSs, DG Tau and V536 Aql and ρ -Oph 102. It is clear that the displacement measured in ρ -Oph 102 is much smaller than in the two CTTSs. Note that in all three sources the displacement in the [OI] λ 6300 line initially increases with velocity. This is a trend seen throughout this thesis from the class I low mass YSOs in Chapter 3 to the Herbig Ae/Be stars in Chapter 5 and this similarity infers that the same outflow mechanism is operating in all these YSOs and ρ -Oph 102 (see also Chapter 3 section 3.3).

To summarise, results presented here support the argument that what is being seen for ρ -Oph 102 is a scaled down version of a CTT flow. The only real difference is that the BD FELRs do not appear to be multi-component. It is often the case for the CTTSs and Herbig Ae/Be stars that one component only is observed. Hence one cannot say for certain as of yet, whether it is the case that BDs do not drive a low velocity disk wind or if observational considerations just make it difficult to observe the LVC. If a typical jet from a BD is not well collimated relative to a CTT jet then the internal line widths of both the HVC and LVC would be larger making it difficult to distinguish between them. Also as density varies with $\frac{1}{\theta}$, where θ is the opening angle of the jet, a larger opening angle could mean that at a fixed distance from the driving source, density is lower for a BD than for a CTTS. This may help to explain why the observed forbidden emission from ρ -Oph 102 arises much closer to the source than seen in a typical CTTSs. The influence of opening angle and density on observed line profiles are covered in depth in Appendix A. Clearly many more sources need to be studied before coming to any firm conclusions. However for the present I propose based on results discussed in this chapter, that what is seen for ρ -Oph 102 is identical to the collimated jets seen in CTTS but on a smaller scale.

6.4.2 Constraining the Theories of Brown Dwarf Formation

As discussed in depth in Chapter 1 the formation mechanisms of BDs are still open to much debate. As we know BDs are sandwiched between low mass stars and planets and the difference between the two strongest competing theories essentially lies in whether BDs are more stellar or planetary in nature. The easiest idea to accept is that they form in the same manner as low mass stars, from the collapse of a molecular core (Shu, Adams, & Lizano, 1987). If they do form from collapsing cores it is possible then that they are just scaled-down versions of TTS or that their low mass results from the fact that they were ejected from their stellar systems their growth was prematurely halted (Reipurth & Bally, 2001). Numerous authors (Jiang, Laughlin, & Lin, 2004; Papaloizou & Terquem, 2001) discuss the possibility that they form in circumbinary disks like planets.

Some of the most interesting work in recent times focuses on how accretion in BDs and the properties of their circumstellar disks, constrain the models of BD formation. If BDs are born in the same manner as low mass YSOs then the way in which they accrete material and the properties of their circumstellar disks should compare favorably to what is well documented for the TTSs. Theories describing BDs as ejected embryos or planets require their disks to be short-lived and small. Evidence to date is strongly in favour of a common formation scenario for low mass stars and BDs. The discovery of outflows and their similarity to CTT flows can only add to this evidence.

Considering the properties of BD disks, Mohanty et al. (2004) find upon studying mid-IR photometry of 3 very young BDs, that disk properties remain the same as we move from the stellar to the sub-stellar regime. They conclude that BD disks have a range of geometries just as in the TTSs. The BD disks also have significant mid-IR excesses and some hint of silicate emission. Also models which best fit their results require the presence of inner disk holes of a few stellar radii comparable again to those detected in the TTSs. It is also reported by Jayawardhana, Ardila, Stelzer, & Haisch (2003) that the inner disk lifetimes of BDs are not dissimilar from those measured for the disks around TTSs. Armitage & Clarke (1997) predict a faster disk evolution for ejected objects.

One notable accretion trend observed in TTSs is that accretion rates decrease with mass (White & Ghez, 2001; Rebull et al., 2000). Muzerolle et al. (2003) focussed on exploring accretion in young BDs and stars in the mass range 0.05-

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$0.2M_{\odot}$. Objects in this mass range are described as very low mass stars (VLMSs). They revealed that disks are relatively common in young VLM objects and that the trend of decreasing mass accretion rate with decreasing mass survives into this mass range. They report a decline of 3-4 magnitudes over $1-0.05M_{\odot}$. This relation between mass and accretion rate is also confirmed by Natta et al. (2004).

Overall the continuity of T-Tauri like accretion into the sub-stellar domain supports a common formation mechanism from solar to sub-stellar masses. Now it seems that we can extend this argument into the realm of outflows. So far as discussed above my results suggest that BD flows are equivalent to CTT flows but simply smaller in magnitude. This new information contributes to the debate regarding the origin of BDs as it strengthens the similarity between BDs and CTTs. However by far the more important consequence of the discovery of an outflow from a BD is that it extends the mass range of objects that show outflows, confirming that outflows are indeed a universal phenomenon amongst objects that are actively accreting onto a disk.

Conclusion

From the results presented here I make the following conclusions.

1. The kinematic and in one case, spatial properties of the FELRs of the two sources discussed concur with the idea that BDs drive outflows that are essentially the same as what is observed for the CTTs but just on a smaller scale. Note that Masciadri & Raga (2004) predict that V_{jet} for BDs and CTTs should be similar and the systemic velocities of the FELs in the spectra of ρ -Oph 102 and LS-RCrA 1 are similar to the typical velocities recorded for the FELRs of CTTs. Note also that offsets in the $[OI]\lambda\lambda 6300, 6363$ lines initially increases with velocity a trend which is seen for forbidden and permitted lines in low mass and Herbig Ae/Be stars (see the preceding three chapters). The fact that this trend is also seen for FELs from ρ -Oph 102 underlines that the same outflow mechanism could be operating here, as in the CTTs and Herbig Ae/Be stars.
2. To date the accretion properties of the BDs have been used as a means of distinguishing between models describing their formation. Now it should be just as possible to consider the properties of their outflows. The major conse-

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quence of the fact that BDs can drive outflows is that theories proposing that outflows are more dependent on accretion properties rather than the nature of the accreting objects are strengthened. Not only do massive objects such as accreting black holes in Active Galactic Nuclei (AGN) drive outflows but sub-stellar BDs do too. This represents a mass range of up to $\sim 10^8 M_{\odot}$.

3. It is now a priority that the number of BDs which have been thoroughly investigated for the presence of outflow activity, be increased. Future plans to observe new sources are discussed in Chapter 7.

Chapter 7

Overall Conclusions and Future Work

Stellar nurseries are the birth places not only of new stars but sub-stellar objects such as BDs and planets also. Protostars are grouped according to their age or evolutionary stage and of course their mass. In Chapter 1 the categorisation of YSOs into low to high mass stars is discussed. That the outflow phenomenon should be a common occurrence amongst protostellar and sub-stellar objects, or that this phenomenon should manifest itself in a similar manner for all objects, is not obvious a priori. While it is long accepted that the outflow stage is a dominant phase in the formation of a young star, gaps exist in our overall understanding of this process, especially when considering activity within the jet launch region. Indeed prior to results presented in Chapter 6 no conclusive evidence supporting the idea that BDs also drive outflows existed. The aim of the research discussed in this thesis, was to compare outflow activity close to the central engines of different types of sources from low mass embedded protostars to Herbig Ae/Be stars and including BDs. The primary method of analysis was spectro-astrometry. Here the main conclusions that can be drawn from this thesis and the future work it inspires, are outlined. The more detailed conclusions taken from the individual studies which make up this body of work, are reviewed at the ends of Chapters 3 to 6.

7.1 Spectro-astrometry: An Important Tool in the Study of Outflows

Without doubt this thesis demonstrates the importance of spectro-astrometry as a tool in the study of outflows. The ability of this technique to extract milli-arcsecond information from a spectrum is wholly utilised to penetrate outflows as close to their point of origin as possible. Four main conclusions can be drawn. Firstly, there is a strong resemblance between outflows launched by protostars of differing mass and evolutionary stage: the LVC and HVC are common features and the spatial properties of these two components, uncovered using spectro-astrometry, are similar in low and intermediate mass YSOs. Secondly, the dominance of the outflow phase is extended into the sub-stellar domain by the discovery that spectro-astrometry can be used to detect outflows launched by BDs. Thirdly, spectro-astrometry is an effective means of disentangling the outflow contribution in HI lines. I have found in particular that $\text{Pa}\beta$ line-wings are a strong probe of outflow activity in CTTSs. Lastly, through a study of the spatio-kinematic properties of permitted lines e.g. $\text{Pa}\beta$, $\text{H}\alpha$, dust holes in the circumstellar disks of the sources are exposed. Each of the above points are explored in more depth in sections 7.2 to 7.5 below. Here some of the ways in which the spectro-astrometric technique can be exploited in the future are reviewed and the method by which it can be evolved to a 2D form is outlined.

Interferometric and Adaptive Optics Techniques

A combination of spectro-astrometry with adaptive optics and interferometric techniques can only but greatly decrease the scales down to which one can recover spatial information. Interferometers like the Keck Interferometer (KI) or the Very Large Telescope Interferometer (VLTI) are equipped with adaptive optics systems which minimise the smearing effects of the atmosphere thus improving the seeing. Combine the influence of the adaptive optics with the large effective apertures of these telescopes and milli-arcsecond spatial resolutions become attainable. Bailey (1998a) discuss how such observations could be analysed with spectro-astrometric methods to extend measurements down to the 100 micro-arcsecond scale. If interferometers are configured to image spectrally dispersed fringes onto a 2D detector at each wavelength the relative position of the source could be determined by the

CHAPTER 7. Conclusions and Future Work

fringe phase and the relative fringe phase could be measured to an accuracy much higher than the fringe separation. Again the fundamental limit would be the photon statistics. At a distance of 150 pc, 100 micro-arcseconds equals ~ 0.015 AU, which is comparable to the radii of the stars being investigated. This offers the exciting prospect of not only being able to investigate outflows on such small scales but also the accretion process. Another intriguing application of such a set-up would be to determine absolute masses for BDs using spatial separation versus time data for BD spectroscopic binaries.

2D Spectro-astrometry

It should be possible to develop the present long-slit spectro-astrometric technique to a 2D form using spectra taken with an Integral Field Unit (IFU). In this way both the offset and position angle of an ELR centroid rather than its displacement in one direction could be determined. This would be in addition to mapping the emission on larger scales. Most spectro-astrometric studies done to date are 1D in the sense that they are taken at one slit position only, generally centred on the source. IFU spectroscopy provides a spectrum simultaneously for each spatial sample of a 2D field and the end product is a datacube with two position axes and a wavelength axis. Such a datacube could also be produced using traditional long-slit spectroscopy, by simply stepping the slit across the extended field. This however would require a large number of separate exposures significantly reducing the throughput in a fixed time. IFU spectroscopy is more efficient as only one exposure is needed to image the whole field. A variety of techniques have been developed to achieve this.

For example the IFU used with the UKIRT, 1-5 μ m Imager Spectrometer (UIST) employs an image slicing technique to divide the original image into long but narrow slices that are re-imaged side by side into a staggered slit. This staggered slit is then passed through the UIST optical system as if it were a long-slit. Each slitlet is 6'' long and 0''24 wide. While the image slicing mirror comprises eighteen segments only fourteen adjacent segments are usable at any one time. Observed side by side these fourteen "slices" cover a 3''3 $\times$ 6'' area of the sky. Collapsing the resultant data cube in the wavelength direction produces a white light image so that the source being observed is seen in the combined infrared light. Figure 7.1 shows a typical datacube, output from UIST used in conjunction with the IFU. It is the active

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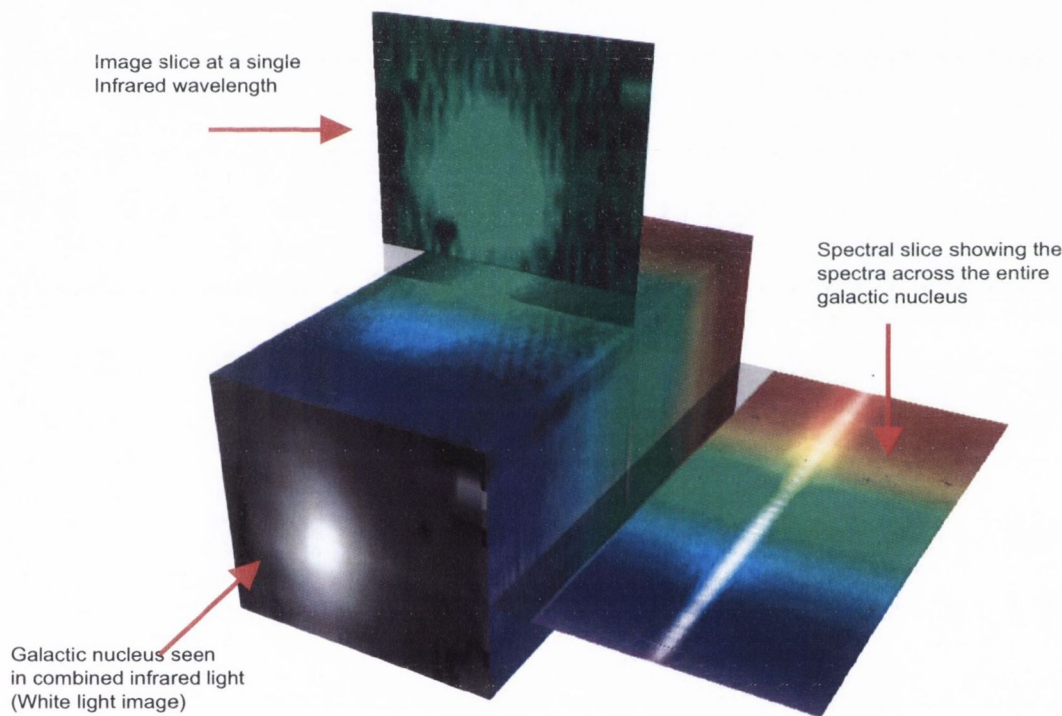


Figure 7.1: The active galaxy NGC1068, imaged using the UIST Integral Field Unit. The greyscale image in the foreground shows the galactic nucleus in white light (integrated in wavelength). Above is an image at a single wavelength (H_2 $2.122\mu\text{m}$, this is one of the hundreds of images that add up to make the white-light image), and to the right is a spectral slice showing a spectrum across the entire nucleus (this time the image is collapsed in one spatial direction).

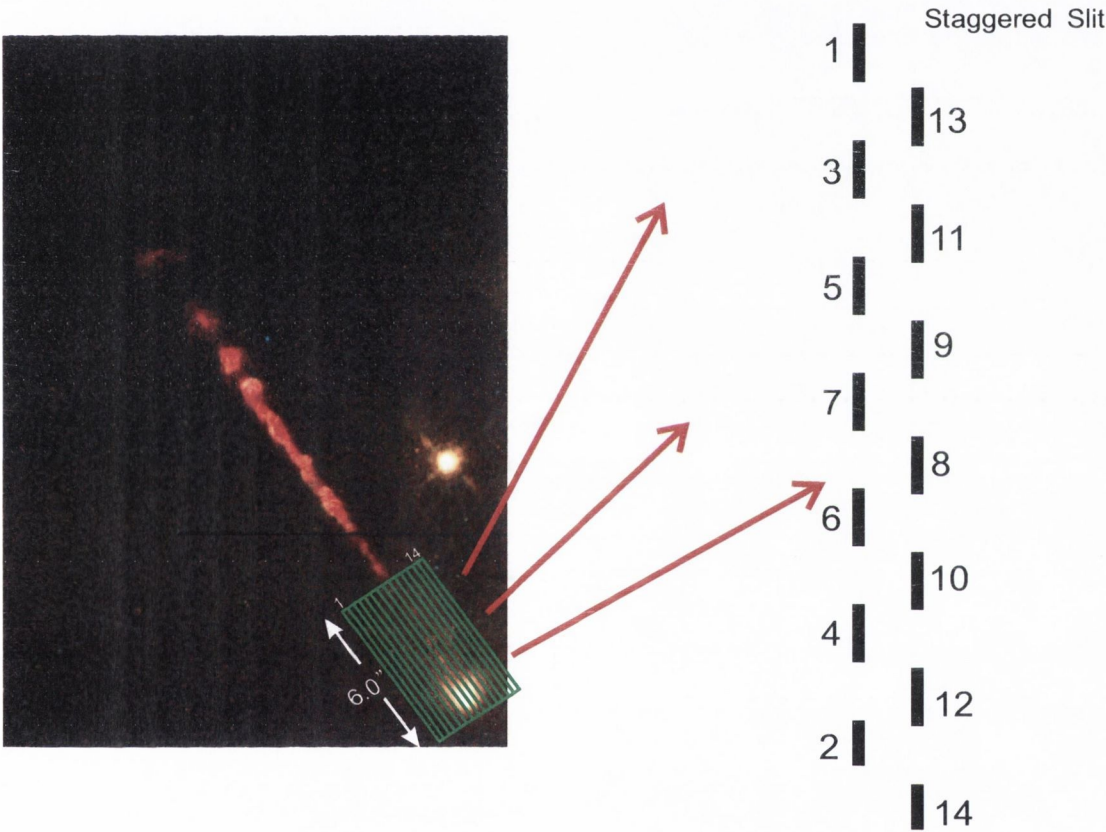


Figure 7.2: Illustration of how a $3''.0 \times 6''$ patch of sky, centred on the collimated outflow from HH 34, is sliced onto a staggered slit using the UIST IFU. A datacube similar to that shown in Figure 7.1 is the output. The image of the outflow was taken with the HST Wide-Field Planetary Camera II. Such an instrumental set-up allows 2D spectro-astrometry of the ELRs associated with this outflow, at its source, to be done.

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galaxy NGC1068 imaged with the IFU and also shown are the galactic nucleus in white light, an image extracted at a single wavelength ($2.122\mu\text{m}$) and a spectral slice showing the spectrum across the entire nucleus.

Figure 7.2 is an illustration of how it is envisioned that such a set-up could be used to study outflows. Again the collimated outflow from the Class I YSO HH 34 is used as an example (see also Figure 2.5). In theory an image centered on the outflow is taken and so the spatial properties can be studied at several positions. In reality not all the spectral slices will have a strong enough continuum for spectro-astrometry. Of course an alternative approach to using an IFU, is to carry out long-slit spectroscopy at two orthogonal P.A.s. In theory however the IFU should determine the same information twice as fast (assuming the same throughput). Moreover the IFU gives spatio-kinematic information over a wider field of view.

7.2 Outflows a Universal Phenomenon

As stated earlier, one of the aspirations of the research reviewed in this thesis is to probe outflow activity close to the central engines of a range of objects from the sub-stellar to the intermediate mass regimes. Altogether four different types of objects are investigated: Class I low mass sources; the more evolved low mass CTTSs; the intermediate mass Herbig Ae/Be stars; and BDs. Similarities are found amongst the outflows driven by the protostellar objects and one discovered from a young BD, ρ -Oph 102. As high mass stars are also known to drive outflows it can be concluded that outflows are a common feature of accreting objects in star forming regions, regardless of mass. Moreover the kinematic and spatial properties of the emission lines (forbidden and permitted) formed in these outflows have similar properties allowing for scaling due to variations in mass loss rates, etc.

The LVC is a common feature of forbidden emission from Class I low mass protostars, CTTSs and Herbig Ae/Be stars. While this was already known for the Herbig Ae/Be stars, the forbidden emission from Class I sources had not been satisfactorily investigated before and the spatial properties of the FELRs of these YSOs had not been explored using spectro-astrometry. No LVC is detected for the FELRs of the BDs discussed in Chapter 6. This does not mean that BDs with outflows do not have a separate poorly collimated disk-wind component, in addition to the high velocity jet. Further observations are required as the sample is

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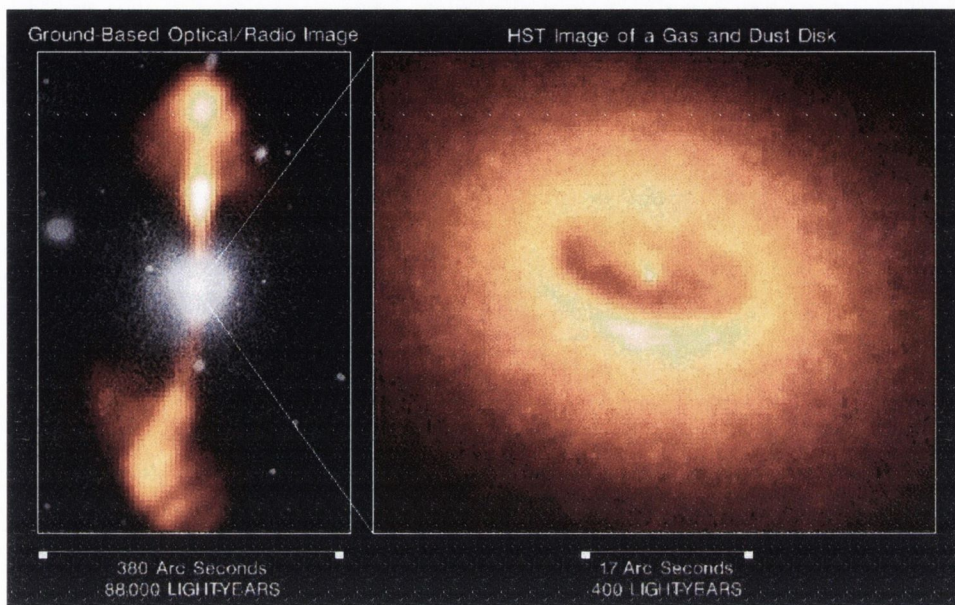


Figure 7.3: The active galaxy NGC 4261 imaged using Wide Field Planetary Camera on the HST (right). Also shown are ground based observations of the jet associated with this AGN (left). Jets associated with AGNs can span distances of up to 10^6 times those from YSOs.

too small. Also note that for all the YSOs probed the HVC is always offset further from the source than the LVC and that for all the FELs and indeed permitted lines, displacement is seen to initially increase with velocity.

It is already known that jets are launched from really massive objects such as black holes in AGNs. These extra-galactic jets are powered by accretion onto a disk surrounding a super massive black hole (M_{BH} as much as a few times $10^8 M_{\odot}$) at the centre of the AGN (see Figure 7.3) and it is believed the magnetic field of the accretion disk collimates the outflowing material into two bipolar jets (Begelman et al., 1984; Ferrari, 1998). The discovery that BDs too are associated with outflows, extends the mass range over which the jet mechanism operates to nearly 10 orders of magnitude. The mechanism is therefore clearly very robust, with the central object merely providing a gravitational anchor. Ultimately the ubiquity of jets may be tied to the presence of magnetic fields in accretion disks and the need for disks to remove angular momentum for accretion to proceed. One can even speculate that planets had jets, assuming they too had accretion disks that ultimately gave rise to their moons.

7.3 Outflows from Young Brown Dwarfs

Spectro-astrometric results presented in Chapter 6 establish that young BDs can launch outflows and that these outflows are scaled-down versions of CTT outflows. By assuming that the escape velocity, and hence the jet velocity, for a BD and a T Tauri star are approximately the same (refer to Masciadri & Raga, 2004) a prediction of where in relation to the source, a collimated outflow from a BD is expected to reach the critical density for forbidden emission can be made. The displacement measured in the [OI] $\lambda\lambda 6300, 6363$ and [SII] $\lambda 6731$ FELs in the spectrum of ρ -Oph 102, agree with the predicted offsets. As underlined above the importance of the discovery that BDs can drive outflows, is that it strongly supports the conjecture that outflows are a universal phenomenon amongst objects that are actively accreting material on to a disk.

Efforts must now be directed towards finding more BDs with outflows and towards imaging these flows. There are many examples of BDs and Very Low Mass Objects (VLMOs) with FEL spectra in the literature (see Tables 7.1 and 7.2). Hence the first approach should be to obtain better optical FEL spectra, taken with the aim of using spectro-astrometry. Intermediate resolutions need to be used to maximise signal to noise and longer exposures on large telescopes taken to increase the strength of the continuum emission.

A second important approach is to consider taking infrared FEL spectra of these sources. As discussed in this thesis infrared FELs (e.g [FeII] $1.644\mu\text{m}$) also form in outflows and map outflow activity. As the continuum emission from a BD will be stronger in the near-infrared than in the optical it may be more practical to study outflows from BDs through spectro-astrometric observations of near-infrared FELs. The average effective temperature of the BDs listed in Table 7.1 is $\sim 2700\text{K}$ and hence emission from these BDs will peak at $\sim 1\mu\text{m}$. The corresponding value for a CTTs is $\sim 4800 \text{ \AA}$. It is not known however if strong near-infrared FELs are a feature of BD outflows.

Lastly imaging BD outflows is not easy. They are extremely faint and the spatial offset, of the brightest forbidden line emission in the outflow is expected to be small. Contamination by light from the BD becomes very important. There are a number of ways around this problem which depend, not only on achieving high spatial resolution but also maximising the contrast of the forbidden lines with respect to the background BD. For example one prospect is to use an integral field

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Object	RA (J2000)	Dec (J2000)	Mass ($M_{\odot}$)	Spec. Ty.	refs
ρ -Oph 30	16 26 21.4	-24 25 59	0.06	M7	1
ρ -Oph 32	16 26 21.7	-24 44 43	0.04	M7.5	1,2
Cha Ha2	11 07 43.00	-77 33 59	0.07	M6.5	1
Cha Ha3	11 07 52.9	-77 36 56.0	0.04	M7	1
Cha Ha6	11 08 40.2	-77 34 17.0	0.05	M7	1
IC 348 478	03 44 35.97	32 11 15.9	0.04	M6.25	2, 4

Table 7.1: Table listing some other BDs with FELS taken from the literature. The RA and Dec, mass and spectral type are given. References are 1: Natta et al. (2004), 2: Muzerolle et al. (2003), 3: Fernández & Comerón (2001) and 4: Jayawardhana, Mohanty, & Basri (2002).

spectrograph (see section 7.1 above) to image the FELRs, hopefully seeing an offset in emission at the source or perhaps even a series of knots.

The Optically Adaptive System for Imaging Spectroscopy (OASIS) which is now at the William Herschel Telescope (WHT) should be suitable. Using OASIS an area of sky between $3''$ and $16''$ is sampled. Unlike UIST described above, where a mirror slicing design is used to divided the original image, the field imaged by OASIS is separated into smaller images or micro-pupils, using an array of micro lenses in the focal plane. Six grisms provide spectral resolutions in the range $1000 < R < 4000$. One of the advantages of OASIS is that it can be used with an AO correction. Lavalley-Fouquet et al. (2000) used OASIS to image the DG Tau micro-jet in $[\text{OI}]\lambda\lambda 6300, 6363$, $\text{H}\alpha$, $[\text{NII}]\lambda 6583$ and $[\text{SII}]\lambda\lambda 6716, 6731$. Despite the seeing reaching $1''$, a spatial resolution of $0''.5$ was achieved thanks to the adaptive optics correction provided by NAOMI (see Figure 7.4) and it may just be possible to produce something similar for ρ -Oph 102. However for most young BDs it will not be feasible to use NAOMI as a V band magnitude greater than 12 is needed for the adaptive optics mode.

7.4 Permitted Hydrogen Lines as Tracers of Outflow Activity

Traditionally, as outlined in Chapter 4, section 4.3.1 it is believed that the primary source of the strong HI lines ($\text{H}\alpha$, $\text{H}\beta$, $\text{Pa}\beta$, $\text{Br}\gamma$ for example) found in the optical and near-infrared spectra of low and intermediate mass YSOs, is emission from hot

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Object	[OI] λ 6300	[OI] λ 6363	H α	[NII] λ 6583	[SII] λ 6716	[SII] λ 6731	refs
ρ -Oph 102	2	0.4	40	0.1	0.07	0.2	1
ρ -Oph 30		0.4	30	<0.1	<0.08	0.08	1,2
ρ -Oph 32			50	0.1	0.12	<0.1	1
Cha Ha2			33	0.06	0.06	<0.1	1
Cha Ha3			10	0.03	<0.1	0.08	1
Cha Ha6			48	0.07	<0.08	<0.08	1
LS-RCrA 1	360	92	25	15	12.4	19.2	1,3
IC 348 478	<9.6	<1.5	22				2

Table 7.2: The equivalent widths (in Å) of the FELs found in the spectra of a sample of BDs. The equivalent width of the H α lines are also given and results for ρ -Oph 102 and LS-RCrA 1 are included for comparison. The < sign indicates that the value is an upper limit. Again references are 1: Natta et al. (2004), 2: Muzerolle et al. (2003), 3: Fernández & Comerón (2001) and 4: Jayawardhana, Mohanty, & Basri (2002).

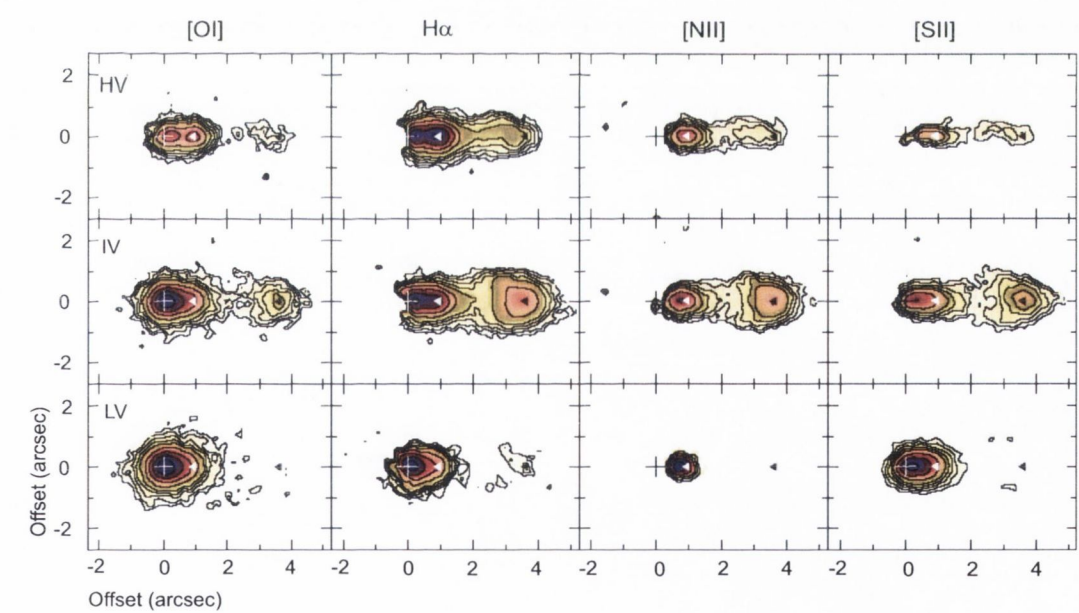


Figure 7.4: Continuum subtracted maps of the DG Tau micro-jet in [OI] λ 6300, H α , [NII] λ 6583 and [SII] λ 6731. Velocity ranges are HV [-400,-250] kms⁻¹(top row), IV [-250,-100] kms⁻¹(middle row) and LV [-100, 10] kms⁻¹(bottom row). Contours in units of 10⁻¹⁸ Wm⁻²arcsec⁻² start at 2.4, increasing by factors of $\sqrt{2}$ for the next 4 levels and by factors of 2 for the following ones. A cross indicates the continuum position (0,0); filled triangles mark the high velocity peak (0.93) and bow-shock apex (3.6). This figure is taken from Lavalley-Fouquet et al. (2000) and illustrates how OASIS can be used to spectroscopically image micro-jets at a high spatial resolution.

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accretion zones. $H\alpha$ of course was known to be emitted by outflows at distances of order of 100 AU from their source i.e. comparable to where the forbidden emission is detected, but very close to the source the situation was not so clear (Calvet, 1997). That HI lines ($H\alpha$ and $Pa\beta$) can be excited in outflows is extremely noteworthy as these emission lines hold advantages over the long established tracers, the FELs, as probes of the central engines of YSOs. Firstly they are formed in regions of high excitation hence they map conditions very close to the source, typically within 15AU. Secondly, unlike the FELs they do not suffer quenching effects caused by high critical densities. An important finding in this thesis is that, for HI lines, spectro-astrometry can be used on a line profile to determine sections of it that may be unequivocally attributed to an outflow.

While it is true that models based on the magnetospheric accretion theory have been the most successful to date in explaining the origin of these ELRs, HI emission line profiles of many CTTSs have features which the magnetospheric accretion model have so far failed to explain (Folha & Emerson, 2001). For example their symmetry, large line wings and broad full width half maxima (again see Chapter 4 section 4.3.2). Profiles exhibiting these features are classified as Type I profiles according to the scheme of Reipurth et al. (1996). Here I have proven that the line wings, in Type I HI profiles, can be attributed to an outflow.

There is much scope for extending the work already done with the $Pa\beta$ line. I have recently observed a large sample of CTTSs and Class I sources at this wavelength using the IFU available with UIST (see section 7.1), after being awarded 16 hours of time. Using the IFU I will be able to perform 2-D spectro-astrometry as outlined above. The $Pa\beta$ emission line profile types of all the CTTSs in the sample are known and I have chosen sources not only with Type I profiles but also with double peaked profiles (Type II or Type III) and inverse P-Cygni profiles (refer to Chapter 4 section 4.3.1). Class I sources drive the most powerful outflows and in this study I will be able to investigate whether $Pa\beta$ also traces outflows from these YSOs. Secondly $Pa\beta$ is an ideal line for use in conjunction with the Astronomical Multiple Beam Recombiner (AMBER) on the VLT (Richichi et al., 2000). AMBER is the NIR/ red focal, imaging and spectroscopic instrument of the VLTI, operating between 1 and $2.5\mu\text{m}$. It has a spectral resolution of 10,000 or 30 km s^{-1} at $1.2\mu\text{m}$. Bacciotti et al. (2003) discuss how observations taken with this instrument will ultimately unveil the launching regions of YSO jets.

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He I Emission Lines as a Probe of Outflows

Another interesting project would be to use spectro-astrometry to probe the origins of the He I emission lines ($\text{HeI}\lambda 5875$ and $\text{HeI}\lambda 6678$) found in the spectra of CTTSs, Herbig Ae/Be stars and also BDs (see Chapter 6). As He I lines have high excitation potentials they must form in regions of high temperature very close to the central protostar. If they also can be excited in outflows they will again provide a very effective means of exploring the jet launch region and a comparison of their spatial properties to the spatial properties of $\text{Pa}\beta$ or $\text{H}\alpha$ say may reveal that they penetrate the central engine even deeper than these lines. Beristain et al. (2001) present a study of the He I and He II emission line profiles of thirty one CTTSs from which they conclude that He I emission from CTTSs can have a dual origin in a magnetospheric inflow and a hot wind. Line profiles are found to be composite and in all cases one of two possible components are present. A broad component which can have its origin in accreting or outflowing gas and a narrow component forming in postshock material at the base of magnetospheric accretion columns. One way of ultimately confirming their findings would be of course to analyse the spectra of their sources for a displacement in the He I ELRs due to the influence of an outflow. However it is very possible that the spatial scales traced by these lines may be too close to the source, even for spectro-astrometry.

7.5 Using Spectro-astrometry to Study Circumstellar Disks

The fact that for two CTTSs and two Herbig Ae/Be stars I was able to use spectro-astrometry to measure a red-shifted offset in the $\text{Pa}\beta$ and/or $\text{H}\alpha$ emission lines, inferring the presence of dust holes in the disks of these sources, only attests to the power and usefulness of this technique. As mentioned numerous times an analogous method had been used prior to these results to detect dust holes in the circumstellar disks of RU Lupi and CS Cha (Takami et al., 2001; Takami, Bailey, & Chrysostomou, 2003). These results, added to the findings presented for the first time in this thesis, extend the number of sources for which spectro-astrometry has been used to find dust holes to six.

In all cases, including RU Lupi and CS Cha, the spectro-astrometric results were compared to the SEDs of the sources. Using the maximum displacement measured

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in the ELR the extent of the dust hole can be estimated and compared to an estimate of the radius of the dust hole taken from the SED. A circumstellar disk has a radial temperature dependence hence the temperature or wavelength at which the lack of excess is seen (recall that a lack of excess is taken to imply the existence of a dust hole) translates to a certain distance from the source. For RU Lupi, CS Cha, and V536 Aql discussed in Chapter 4 section 4.3.4, a good agreement is seen. However this method of comparison fails for the two Herbig Ae/Be stars discussed in Chapter 5 section 5.3.3. Here a radial temperature dependence derived for the circumstellar disk of a CTTS is used to estimate the radius of the disk gaps and this may not be applicable to the disk of an intermediate mass star. Moreover, note that I assumed a geometrically thin, optically thick passive disk heated by a central source ($0.5 \leq q \leq 0.75$). In reality those disks are accreting and may be flared. Such disks tend to be hotter at a given radial distance than passive ones, hence even if they contain an inner dust hole, it may not be obvious from their SED. This could also explain why no evidence for a dust hole is seen in the SED of LkH α 321.

Overall this result is very promising and is certain to lead to some interesting new work. As outlined in the relevant sections in Chapters 4 and 5 it is postulated that these dust holes or disk gaps occur due to the clearing of dust grains but not necessarily gas, either as a result of their destruction or by coagulation of the grains into larger bodies. A gradual fall off in the density of small grains with proximity of the source could also explain why the red-shifted outflow offset is less in H α in comparison to Pa β . Overall how transparent the disk is to a certain line at a given location depends on the wavelength of the line and the size of the dust grains in the location. This explains why H α becomes obscured at a shorter distance from the protostar than Pa β .

If this scenario can indeed be used to account for the presence of dust holes in the circumstellar disks of YSOs and the results seen with spectro-astrometry, then it should be possible to construct a transparency profile of a circumstellar disk through a study of the displacement of several different HI (and perhaps even He I see section 7.4) lines of known intensity. The place to begin would be to look at a source where the existence of a disk hole/gap is suggested from the study of more than one line (V536 Aql) and then study the displacement of several other HI (or He I) ELRs. For example H β (4861.3 Å), Br 12 (1.6114 μ m) or He I (1.088 μ m). If all these lines were formed in one outflow then they should trace the red-shifted lobe of the outflow out to slightly different distances.

Final Thought

Clearly spectro-astrometry is an excellent diagnostic tool, recovering information on scales that are much smaller than the “seeing”. Using spectro-astrometry to investigate the central engines of numerous young stellar objects at different wavelengths, has uncovered new and interesting information concerning their outflows and indeed their circumstellar disks in which new planets may eventually form. It is also now clear that spectro-astrometry is in effect winning the race when it comes to finding outflows launched by sub-stellar BDs. Moreover it is apparent that this technique has been much under-utilised to date. New telescopes like the James Webb Space Telescope or the California Extremely Large Telescope are designed to push the boundaries of observational astronomy way beyond our present limitations and will as a result answer many of the important questions which have been touched on throughout this thesis, questions which ultimately relate to the way in which our own solar system formed. However while we await the arrival of such powerful telescopes, it is fair to predict that spectro-astrometric studies will continue to deliver exciting new results, adding to our understanding of how stars and planets are born and the role outflows have to play in these processes.

Appendix A

Forbidden Lines of YSO Jets

Mass Loss Rate

Figure A.1 below depicts a jet, represented by a filled cone of opening angle θ and radius r_{jet} . The mass of jet material dM passing the point A is given by

$$dM = \rho dU \quad (A.1)$$

where U is the volume of material and ρ is the density of the material, at A . The mass loss rate through a cross-section of the cone, at A , is

$$\frac{dM}{dt} = \rho \frac{dU}{dt} \quad (A.2)$$

or

$$\frac{dM}{dt} = \rho \pi r_{jet}^2 \frac{dL}{dt} \quad (A.3)$$

as the volume of the cross-section of the cone is approximated by a cylinder of radius r (where r is the radius of the jet r_{jet} at A) and length dL . For a constant velocity outflow

$$dL = V_{jet} dt \quad (A.4)$$

hence

$$\dot{M} = \rho \pi r_{jet}^2 V_{jet} \quad (A.5)$$

From Figure A.1, $\tan \theta = \frac{r_{jet}}{L}$ or for small values of θ (in radians) $\theta = \frac{r_{jet}}{L}$, giving

$$\dot{M} = \rho \pi \theta^2 L^2 V_{jet} \quad (A.6)$$

Observationally, the mass loss rate at a certain point along a jet, can be estimated by considering the following equation (Nisini, Bacciotti, Giannini, Massi, Eislöffel, Podio & Ray, 2005),

$$\dot{M}_{jet} = \mu m_H n_H \pi r_{jet}^2 V_{jet} \quad (A.7)$$

where μ is the average atomic weight (1.24), m_H is the proton mass and n_H is the total hydrogen density. Here the density of the jet is approximated by the density of hydrogen atoms. The number of hydrogen atoms per cm^{-3} is given by

$$n_H = \frac{n_e}{x_e} \quad (A.8)$$

where n_e and x_e are the electron density and ionisation fraction respectively. The electron density is measured from line ratios of certain forbidden lines. The ratio of the [SII] $\lambda\lambda 6716, 6731$ lines is sensitive to electron densities in the range $50\text{--}2 \times 10^4 \text{ cm}^{-3}$, and the ratio of the Fe lines at $7715 \text{ \AA}$ and $8617 \text{ \AA}$ is sensitive to densities in the range $\sim 10^5$ to 10^7 cm^{-3} . The ionisation fraction can be derived from the observed ratio of the $\frac{[OI]\lambda\lambda 6300, 6363}{[NII]\lambda\lambda 6583, 6548}$ lines and the electron temperature (T_e) from the $\frac{[OI]\lambda\lambda 6300, 6363}{[SII]\lambda\lambda 6716, 6731}$ ratio.

Table A.1 gives the derived values of $\dot{M}_{jet}$ for the first two knots in the small-scale jet from DG Tau. The FEL spectrum of DG Tau obtained with the IDS on the INT and discussed in Chapter 4 was used to estimate r_{jet} , V_{jet} and n_e at $1''$ and $4''$. The values of x_e given in Table A.1 were taken from Dougados et al. (2002). The radius, velocity and electron density for DG Tau at $1''$ and $4''$ are also given in Table A.1. Using equation A.7 above I measure the mass loss from DG Tau to be $1 \times 10^{-7} \text{ M}_{\odot}\text{yr}^{-1}$ at $1''$ or (140 AU) and $2 \times 10^{-8} \text{ M}_{\odot}\text{yr}^{-1}$ at $4''$ or (560 AU). This calculation has been done several times for the DG Tau jet and is given at $\sim 1.4 \times 10^{-8} \text{ M}_{\odot}\text{yr}^{-1}$ by Dougados et al. (2002), $\sim 5 \times 10^{-8} \text{ M}_{\odot}\text{yr}^{-1}$ by Bacciotti et al. (2002) and at $\sim 3 \times 10^{-7} \text{ M}_{\odot}\text{yr}^{-1}$ by Hartigan et al. (1994).

The above method for estimating $\dot{M}_{jet}$ assumes that the knot is uniformly filled at the derived density and thus does not take into account the volume filling factor. Bacciotti & Eislöffel (1999) also discuss the importance of including the shock

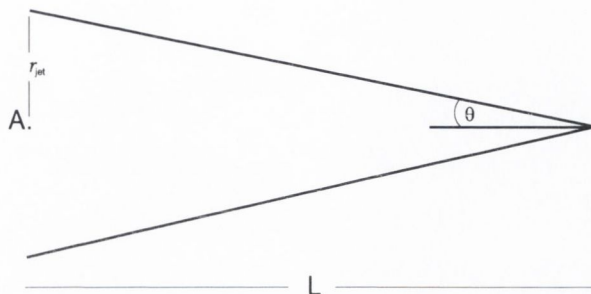


Figure A.1: Jet is represented by a filled cone of opening angle θ and radius r_{jet} .

L(arcsec)	r_{jet} (arcsec)	V_{jet} (kms $^{-1}$)	n_e ($10^4 cm^{-3}$)	x_e	$\dot{M}_{jet}$ ($10^{-8} M_{\odot} yr^{-1}$)
1	0.76	175	1.5	0.45	15
4	1.2	218	0.15	0.8	3

Table A.1: Table listing the radius, radial velocity, electron density, ionisation fraction and thus mass loss rate for knots A and B of the DG Tau jet.

compression C in the calculation of the total jet density. C is defined as the ratio between the post and pre-shock densities averaged over the [SII] emission region and the compression is factored in by multiplying n_H by $C^{0.5}$. An alternative method for estimating the mass flux involves using the luminosity of selected forbidden lines ([OI], [SII], [FeII]) as a diagnostic of the mass loss. As these line are optically thin their luminosity is proportional to the mass of the emitting gas, thus the volume filling factor is implicitly accounted for and is given by the ratio of the values of $\dot{M}_{jet}$ measured using the two methods. Hartigan et al. (1994b) measure mass loss rates using both methods and find a good agreement with the inclusion of the C factor.

Forbidden Emission Line Flux and Critical Density

Forbidden emission lines play a vital role in the cooling of the shocks, which result from the interaction of YSO jets with their ambient medium (see Chapter 1 section 1.2.1). It is the velocity of the interacting jet that determines the temperature of the material behind the shock front, which in turn determines what elements are ionised (and to what extent). For example hydrogen is largely ionised for a shock velocity $V_s \geq 50 \text{ kms}^{-1}$, i.e. a gas temperature of $\sim 4 \times 10^4 \text{ K}$. Oxygen will be ionised to O^+ under these conditions yet shock velocities of $V_s \geq 100 \text{ kms}^{-1}$ are needed to

ionise oxygen largely to O^{++} . Radiative shocks can be divided into cooling zones where different species dominate depending on temperature or the distance from the shock front. The structure of such a shock is illustrated in Figure 1.10. It is the fact that these shocks radiate so strongly in the forbidden lines that makes these transitions so useful in the analysis of outflows.

Forbidden transitions are collisionally excited. As the transition lifetimes are relatively very long (~ 100 s), there is a strong probability that if the emitting material is dense enough, decay will occur via collisional de-excitation, long before enough time has passed for radiative decay. As a result, FEL flux which shall be discussed here in more depth, has an important density dependence. The critical density (n_{cr}) for forbidden emission is defined as the density at which the downward collisional and radiative rates are equal. Some typical values of n_{cr} at T_e equaling 10,000 K, are, $6 \times 10^4 \text{ cm}^{-3}$ ([NII] λ 6584), $2 \times 10^4 \text{ cm}^{-3}$ ([NII] λ 6548) and $6 \times 10^3 \text{ cm}^{-3}$ ([SII] λ 6731, 6716). The [OI] $\lambda\lambda$ 6300,6363 doublet has a much higher critical density ($\sim 2 \times 10^6 \text{ cm}^{-3}$) hence it will be seen closer to the protostar than [SII] $\lambda\lambda$ 6716,6731 say, as results discussed in this thesis clearly demonstrate. This section is a semi-quantitative discussion of FEL flux from YSO jets and its dependence on electron density and on how well the emitting region is sampled spatially.

Imagine a knot in an outflow which can be approximated by a cube of side X (see Figure A.2). The total flux from that cube F will be a function of electron density, electron temperature, X and the distance to the knot (from the observer), D . The surface flux B (per unit area, per second, per unit solid angle) is given by

$$B = \frac{\varepsilon(n_e, T_e)X}{4\pi} (\text{ergs/s/cm}^2/\text{sr}) \quad (\text{A.9})$$

and $\varepsilon(n_e, T_e)$ is the emissivity per unit volume and the line emission is optically thin. The total flux

$$F = \int_0^\Omega B d\Omega \quad (\text{A.10})$$

where Ω is the solid angle. Hence

$$F = \frac{\varepsilon(n_e, T_e)X^3}{4\pi D^2} (\text{ergs/s/cm}^2) \quad (\text{A.11})$$

The above calculation, which assumes that the cube is resolved by the telescope,

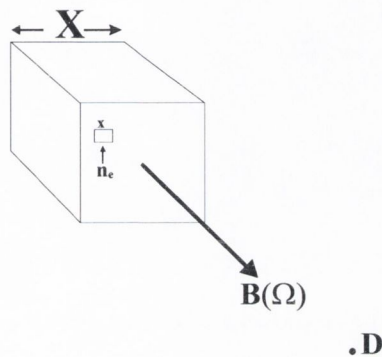


Figure A.2: Consider the idealised case of a resolved knot in a YSO jet, approximated by a cube of side length X . The knot consists of j unresolved cubes of side length x and electron density n_e . A telescope that subtends a solid angle Ω detects all the emission from the knot at a distance D . The total flux from this knot, $F = \int_0^\Omega B d\Omega$, where $B(\Omega)$, is the surface flux.

shows that B is independent of distance to the observer.

For a simple two level atom approximation and neglecting collisional de-excitation (i.e. at the low density limit), the forbidden line emissivity per unit volume is

$$\varepsilon(n_e, T_e) = n_2 A_{21} h \nu_{21} \quad (\text{A.12})$$

where A_{21} is the Einstein coefficient (probability of a radiative transition from level 2 to 1) (Osterbrock, 1989; Edwards et al., 1987). The balance between the rate of collisional excitation out of the ground state and the rate of collisional and radiative de-excitations out of the excited state, is given by

$$n_1 n_e q_{12}(T) = n_2 n_e q_{21}(T) + n_2 A_{21} \quad (\text{A.13})$$

or

$$\frac{n_2}{n_1} = \frac{n_e q_{12}(T)}{A_{21}} \left[\frac{1}{1 + \frac{n_e q_{21}(T)}{A_{21}}} \right] \quad (\text{A.14})$$

where $q_{12}(T)$ and $q_{21}(T)$ are the collisional excitation and de-excitation rates re-

spectively. Also

$$\frac{n_2}{n_1} = \frac{q_{12}(T)}{q_{21}(T)} \left[\frac{1}{1 + \frac{A_{21}}{n_e q_{21}(T)}} \right] \quad (\text{A.15})$$

Hence

$$\varepsilon(n_e, T_e) = n_2 A_{21} h\nu_{21} = n_e n_1 q_{12}(T) h\nu_{21} \left[\frac{1}{1 + \frac{n_e q_{21}(T)}{A_{21}}} \right] = n_e n_1 q_{12}(T) h\nu_{21} \left[\frac{n_{cr}}{n_{cr} + n_e} \right] \quad (\text{A.16})$$

as the critical density defined above is given by

$$n_{cr} = \frac{A_{21}}{q_{21}(T)} \quad (\text{A.17})$$

In the low density regime ($n_e \ll n_{cr}$), every collisional excitation is followed by the emission of a photon and

$$\varepsilon(n_e, T_e) = n_e n_1 q_{12}(T) h\nu_{21} \quad (\text{A.18})$$

For $n_e \ll n_{cr}$, collisional de-excitation is obviously negligible. For electron densities $n_e \gg n_{cr}$,

$$\varepsilon(n_e, T_e) = n_1 \frac{w_2}{w_1} e^{-\chi/kT} A_{21} h\nu_{21} \quad (\text{A.19})$$

as

$$\frac{n_1}{n_2} \approx \frac{q_{12}(T)}{q_{21}(T)} \quad (\text{A.20})$$

and

$$\frac{q_{12}(T)}{q_{21}(T)} = \frac{g_2}{g_1} e^{-\chi/kT} \quad (\text{A.21})$$

where g_1 and g_2 are the statistical weight of the lower and upper levels respectively. See equation 1.16 above and Osterbrock (1989) section 3.5. Overall the FEL flux is proportional to n_e at the low density limit and is maximised at $n_e = n_{cr}$. For $n_e \gg n_{cr}$ the flux becomes independent of density and in these conditions the level populations are said to be thermalised.

Osterbrock (1988) illustrated the dependence of the FEL flux on critical density using the example of a hypothetical forbidden line at 5000 Å. Figure A.3 taken from Osterbrock (1988) illustrates the photon emission rate per ion as a function of n_e for a typical forbidden line and a typical permitted line. The critical density for the FEL is the point on the graph where the photon emission rate per ion goes

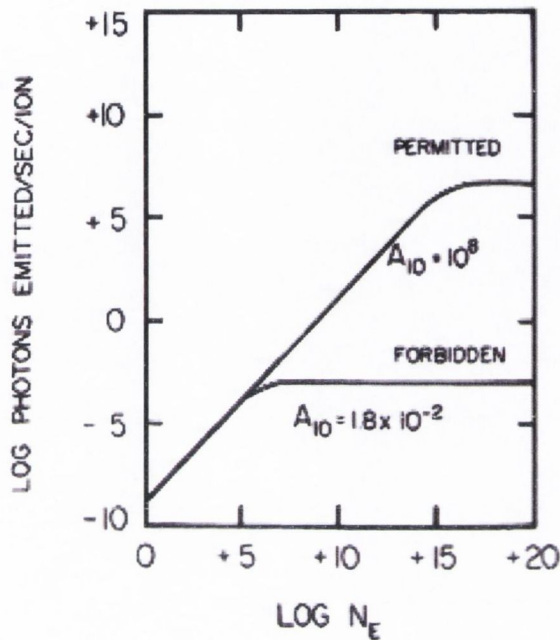


Figure A.3: Photon emission rate per ion as a function of n_e for a typical forbidden line (lower curve) and a typical permitted line (upper curve), taken from Osterbrock (1988)

over from increasing proportionality to n_e and becomes essentially constant. The critical density for permitted lines is much larger ($\approx 10^{15} \text{ cm}^{-3}$), hence in typical laboratory situations the FELs are weaker by factors of $\sim 10^9$ than the permitted lines.

How good a measure of n_e and T_e the line ratios discussed in the previous section are depends somewhat on how well sampled the emitting region is spatially. If for the cube of emitting material, X is $\gg$ the spatial resolution element, then estimates of n_e and T_e and hence of the surface flux B will be reasonably accurate. If on the other hand X is $\ll$ the spatial resolution element, the surface emission line flux is likely to be over or under-estimated depending on the density of the material surrounding the knot. If the resolution is low enough it may even be impossible to distinguish between two very close knots say. For this reason it can prove difficult to derive an accurate estimate of the mass loss rate for a knot in a jet which lies at the source. Lavalley-Fouquet et al. (2000) studied the small scale jet from DG Tau with a very high spatial resolution (see also Chapter 7 section 7.3) and thus provided line ratios with a higher spatial resolution than had been achieved before.

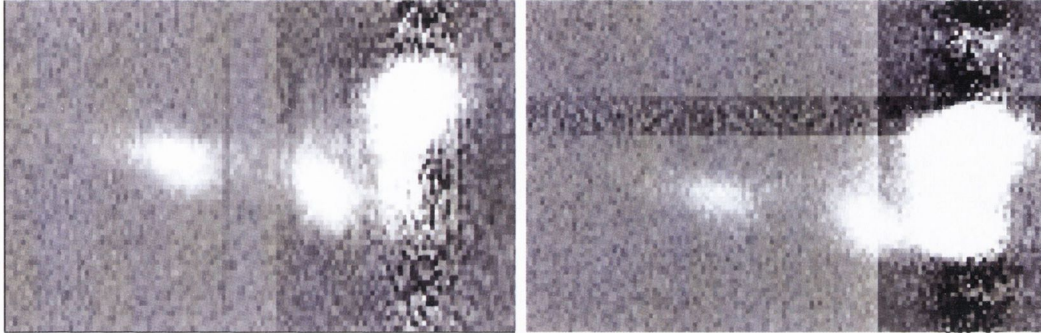


Figure A.4: The small-scale jet from DG Tau in the forbidden lines of [SII] λ 6731 (left) and [OI] λ 6300 (right). Due to the higher critical density of the [OI] line the jet is brighter in [OI] close to the source and the furthest knot along the jet, Knot C is brightest in [SII]. From the [OI] image it is clear that brightness fades with distance as a result of the falling density. The darker grey regions are where the continuum and [OI] night sky line, were removed using a standard IRAF routine.

As a result it was possible for them to study how n_e , T_e and x_e varied with distance along the jet axis, within a distance of only $4''$ from the star.

The dependence of the FEL flux on density easily explains why the brightness of a YSO jet fades quickly with distance. Consider a fully spatially resolved jet, again represented by a cone of opening angle θ . The inner region ($n_e > n_{cr}$) spans say $3''$ from the driving source and in the outer region n_e falls below n_{cr} . Figure A.3 illustrates what one should expect to see from such a set-up. The FEL flux is essentially constant beyond the critical density but at n_e less than the critical density flux quickly drops off as n_e decreases. How well the cross-over between $n_e > n_{cr}$ and ($n_e < n_{cr}$) is seen depends on how well the jet is spatially sampled. For example it is obvious that in the case that one observes with a spatial resolution of $1''$, the flux will show no change over a distance of $1''$ and it will not be possible to determine where the density goes above the critical density, to a high accuracy. In general n_e and hence F falls off with $\frac{1}{L^2}$. L is the distance along the axis of the jet and this dependence assumes an idealised jet with constant values of $\dot{M}$ and V_{jet} (refer to equation 1.6). Lavalley-Fouquet et al. (2000) show that n_H in the DG Tau jet obeys an approximate $\frac{1}{L^2}$ law.

In figure A.4, images of the DG Tau jet in [SII] λ 6731 and [OI] λ 6300 are presented. These images illustrate well the considerations regarding density discussed above. The critical density for [OI] λ 6300 is larger by a factor of ~ 100 than for [SII] λ 6731 hence emission peaks closer to the source for [OI] λ 6300 than for

[SII] λ 6731. In Figure A.4 it is seen that [OI] emission is strongest for knots A and B. Knot C is strong in [SII] but weak in [OI]. The [OI] line flux decreases with L below n_{cr} . Very close to the star the density will be great enough for the forbidden emission to be completely suppressed. Due to the high spatial resolution needed it is not possible to detect this point from a typical longslit spectrum. However spectro-astrometric results presented in Chapter 4 do give some indication of how close to the star this density will be reached. Pa β is a better tracer of outflows at high spatial resolution simply because it doesn't suffer from the effects of the critical density. The Pa β emission from the V536 Aql jet is seen through the hole in the disk of V536 Aql at a distance of $\sim 0''.1$ where there is no forbidden emission, as densities are too high.

Line Profiles

In this section the approximation of a stellar jet by a filled cone of opening angle θ is continued and used as a basis for a discussion of the dependence of the width and shape of the jet line profiles on θ and I the inclination angle of the jet with respect to the line of sight. Figure A.5 taken from Edwards et al. (1987) illustrates well the problem under consideration. Here each point P has a velocity

$$V_r(r, \theta, \phi) = -V(\theta) \cos \beta \quad (\text{A.22})$$

where $\beta = I + \theta$ and

$$V(\theta) = V_{max} f(\theta) \quad (\text{A.23})$$

For a constant velocity jet with all velocity vectors having the same length, $f(\theta) = 1$. Using the derivation of Beals (1931) one can firstly consider analytically the special case of $I = 0^\circ$. For this case, the divergence of the jet streamlines (as defined by θ) is the dominant mechanism by which the lines are dynamically broadened.

Following the Beals (1931) solution and using Figure A.6, the area of the emitting zone of radius $R \sin \theta$ and width $d\theta$, is $2\pi R^2 \sin \theta d\theta$. The number of atoms passing through the zone per second can be taken as

$$N = 2\pi n R^2 \sin \theta d\theta \quad (\text{A.24})$$

where n is the number of atoms ejected per second. The energy contribution of N

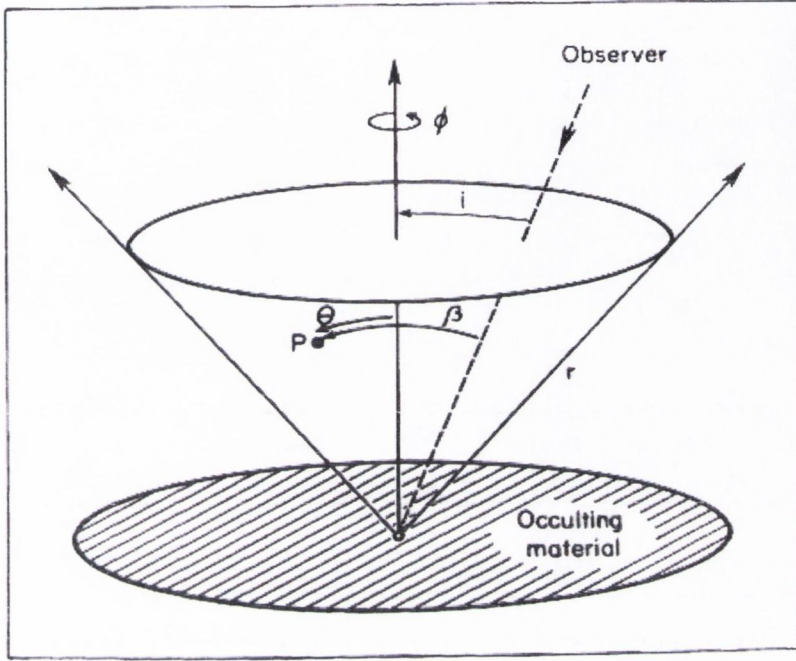


Figure A.5: Geometric parameters of a jet modelled by a filled cone of radius θ . This is taken from Edwards et al. (1987).

is

$$dE = K2\pi nR^2 \sin \theta d\theta \quad (\text{A.25})$$

where K is some undetermined constant. As given above in equation A.9, the radial velocity for an observer at O ($I = 0^\circ$ and $f(\theta) = 1$) is

$$V_r = -V_{max} \cos \theta \quad (\text{A.26})$$

Solving for $d\theta$

$$d\theta = \frac{dV_r}{V_{max} \sin \theta} \quad (\text{A.27})$$

and substituting this into equation gives

$$dE = \frac{const}{V_{max}} dV_r \quad (\text{A.28})$$

This formula for dE represents the energy emitted in the velocity range V_r to $V_r + dV_r$ and as dV_r is constant, the line profile is a flat topped profile which covers the velocity range $V_{max} \cos 0$ to $V_{max} \cos \theta_{max}$. For example in Figure A.9 the width of

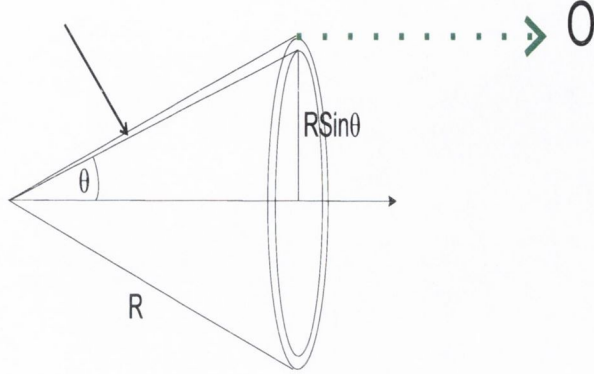


Figure A.6: Illustration for the Beals (1931) derivation for an emitting region represented by a ring of width $d\theta$, with $I = 0^\circ$.

the profile for $I = 0^\circ$ is $-\cos 60^\circ$.

A second broadening mechanism is introduced to the problem when one examines the effect of having values of I larger than 0° . The shape and width of the line profiles for $I > 0^\circ$ have been discussed analytically by both Appenzeller, Öestreicher, & Jankovics (1984) and Kwan & Tadamaru (1995). When I is $> 0^\circ$ the line profile width, radial velocity and strength, depends on how I compares with θ and this dependence is described by

$$\Upsilon(V) = \frac{\pi}{2} - \arcsin \frac{[V_{max} \cos I + V \cos \theta]}{[(V^2 - V_{max}^2)^{0.5} \sin I]} \quad (\text{A.29})$$

where Υ is the line intensity. For I and θ equal to 45° , the above equation simplifies to

$$\Upsilon(V) = \frac{\pi}{2} - \arcsin \frac{[1 + V/V_{max}]}{[(1 - V^2/V_{max}^2)^{0.5}]} \quad (\text{A.30})$$

Edwards et al. (1987) solved this problem numerically and produced results for the case of a constant velocity wind (as described above) which match those derived by Appenzeller, Öestreicher, & Jankovics (1984) and Kwan & Tadamaru (1995). A grid of 5000 θ points and 49 evenly spaced velocity bins was used and values of $I = 0^\circ, 10^\circ, 30^\circ, 45^\circ, 60^\circ$ and 80° , with $\theta = 45^\circ$ examined. Adopting the same approach, the line profiles for three cones of differing opening angles, $\theta = 30^\circ, 45^\circ$ and 60° were modelled for values of I between 0° and 90° (see Figures A.7, A.8, A.9). A constant velocity wind with $V_{max} = 1$, $f(\theta) = 1$ was used and the resultant profiles clearly illustrate how the line profile is dynamically broadened as the divergence of

$$\theta = 30^\circ$$

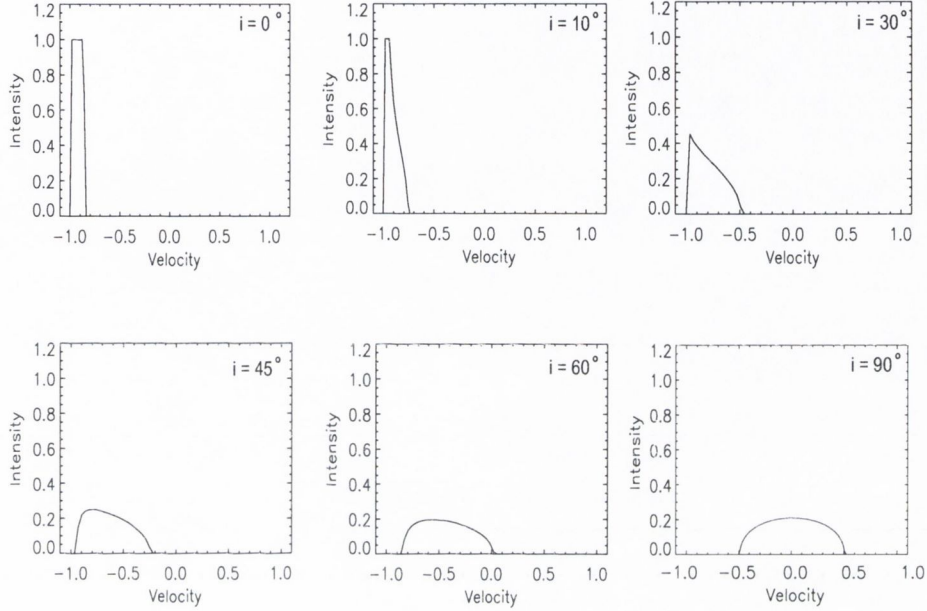


Figure A.7: Family of line profiles for a filled cone of $\theta = 30^\circ$ and I between 0° and 90° and a constant velocity.

the jet streamlines i.e., θ is increased and as I is increased from 0° to 90° . Next the cases of an accelerating jet ($V = -\cos \beta * (0.1 + 0.9R)$; intensity $\propto 1/R^2$) and a decelerating jet ($V = -\cos \beta / (1.0 + R)$; intensity $\propto 1/R^2$), represented by a cone of $\theta = 45^\circ$ were modelled. The same values of I were taken and the resultant profiles are presented in Figures A.10 and A.11. In all cases intensity which has a R^{-2} dependence, is normalised to the intensity at $I = 0^\circ$.

As described, the modelled line profiles are broadened due to the divergence of the jet streamlines and the effect of making $I > 0^\circ$. Other methods of broadening the line profile, kinematically, can be introduced by considering the effect of decreasing the length of the velocity vectors with distance from the jet axis. In other words $f(\theta)$ is no longer constant but a function of θ . The effect of making

$$f(\theta) = 1 - 0.8 * \theta / \theta_{max} \quad (\text{A.31})$$

is shown in Figure A.13 for cones of $\theta = 30^\circ$, 45° and 60° . See also Figure A.12. For cones with zero inclination the full width zero intensity of the profiles, is broadened, however the FWHM decreases. For values of $I > 0^\circ$ the linewidth becomes narrower

$$\theta = 45^\circ$$

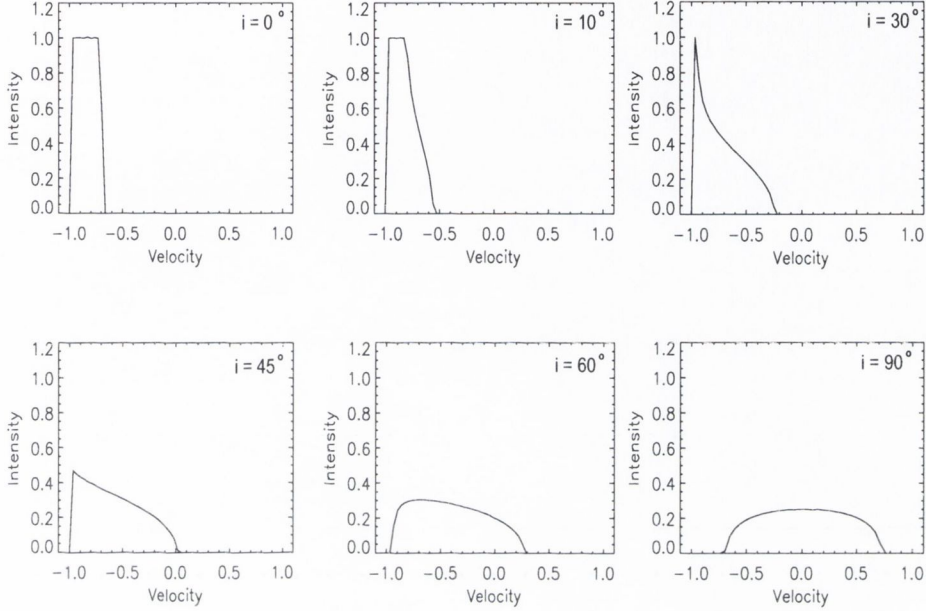


Figure A.8: Family of line profiles for a filled cone of $\theta = 30^\circ$, I between 0° and 90° and a constant velocity.

and a double peaked structure develops. Giving the length of the velocity vectors a θ dependence has the effect of making the wind latitude dependent. See Edwards et al. (1987) for a complete discussion of latitude dependent wind models. A second possibility is the introduction of a turbulent boundary layer between the jet and the ambient medium. Within this layer all values of V between V_{max} and zero are found and this will cause a smearing of the line profile at the edges making the profile essentially bell-shaped. The different methods of broadening discussed so far will dominate the thermal broadening such that its effect is essentially negligible. The thermal broadening is given as

$$\Delta V_{th} = 2[\ln 2(\frac{2kT}{\mu})^{0.5}] \quad (A.32)$$

and Mundt et al. (1990) estimate ΔV_{th} for $H\alpha$, at $\approx 22 \text{ kms}^{-1}$ for $T \approx 10^4 \text{ K}$. ΔV_{th} will be considerably lower $\sim 1 \text{ kms}^{-1}$ for the forbidden lines of [OI], [NII] and [SII].

It is possible to derive the opening angle of a jet from the measured linewidth of the HVC of a forbidden line profile, once some simple assumptions are made (Mundt

$$\theta = 60^\circ$$

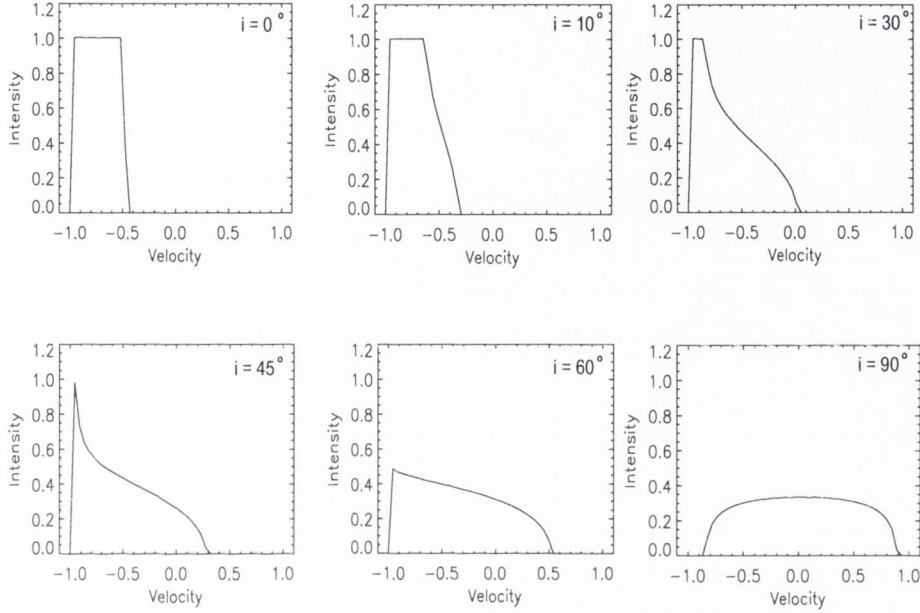


Figure A.9: Family of line profiles for a filled cone of $\theta = 60^\circ$, I between 0° and 90° and a constant velocity.

et al., 1990; Eislöffel et al., 2000). Again the jet is approximated by a homogenously filled cone with the same velocity, V_{max} along the diverging streamlines and

$$\theta = \arcsin [\Delta V_{HVC} / (V_{HVC} * f_{1/2} * \tan I)] \quad (\text{A.33})$$

ΔV is corrected for instrumental broadening and $f_{1/2}$ (0.9) is the correction factor to convert full width at zero intensity into FWHM (Mundt et al., 1990). Hirth, Mundt, & Solf (1994b) derive the opening angle of the CW Tau jet using the above formula. For CW Tau the low and high velocity components are clearly separated and the above authors estimate a value of I equal to $\approx 70^\circ$, from

$$I = \arccos [V_{HVC} / V_{max}] \quad (\text{A.34})$$

where V_{max} is the typical velocity of a jet (taken at 300 kms^{-1}) and V_{HVC} is the radial velocity of the high velocity component (100 kms^{-1}). Using $\Delta V = 60 \text{ kms}^{-1}$ a value of $\theta = 14^\circ$ is measured. A similar calculation can be done for L1551-IRS5, using the [FeII] FEL (see Chapter 3 section 3.2.3). In this case $V_{max} = 350 \text{ kms}^{-1}$

$\theta = 45^\circ$ accelerating outflow

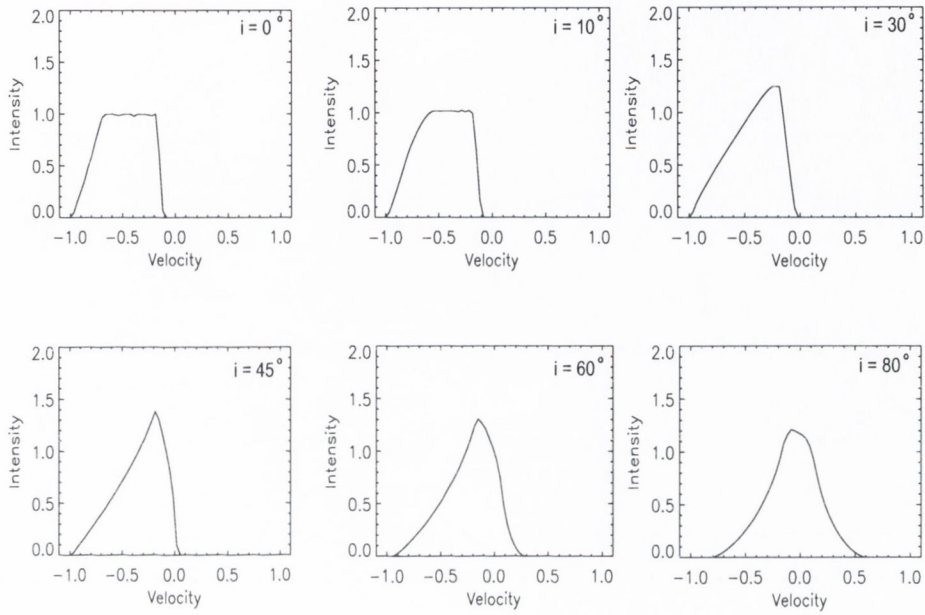


Figure A.10: Family of line profiles for an accelerating jet, approximated by a filled cone of $\theta = 45^\circ$ and I between 0° and 90° .

$\theta = 45^\circ$ decelerating outflow

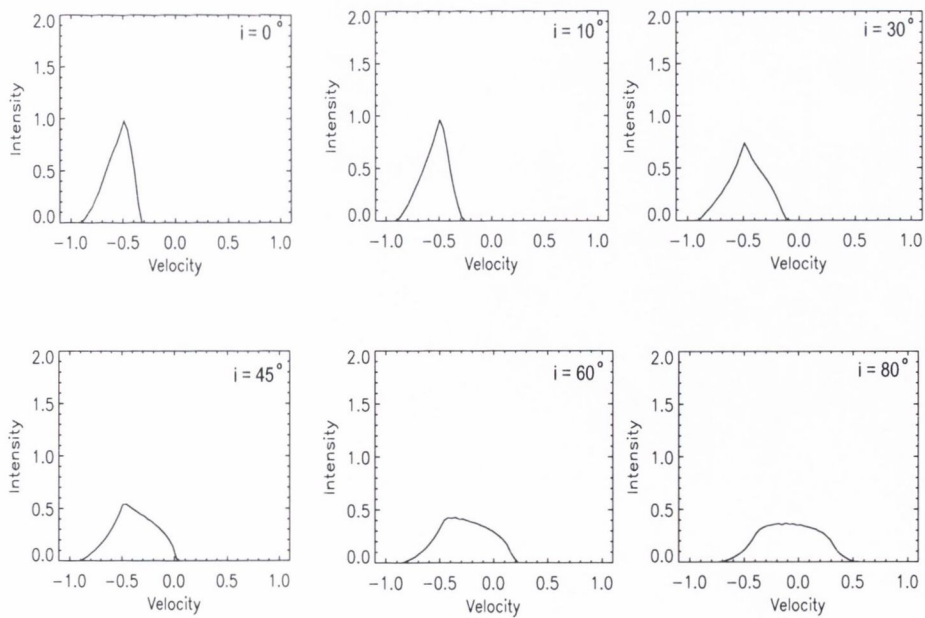


Figure A.11: Family of line profiles for a decelerating jet, approximated by a filled cone of $\theta = 45^\circ$ and I between 0° and 90° .

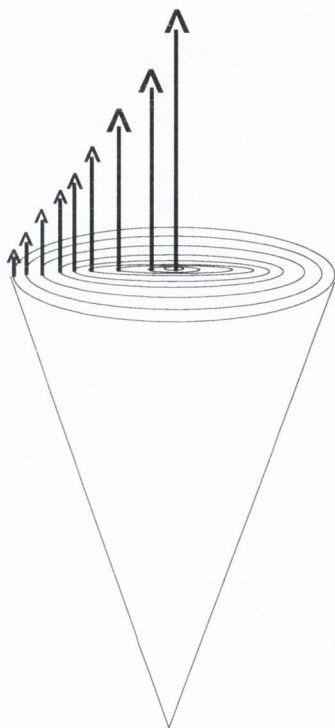


Figure A.12: Illustration of a latitude dependent wind represented again by a filled cone. The velocity vectors decrease with increasing θ .

$I = 30^\circ$

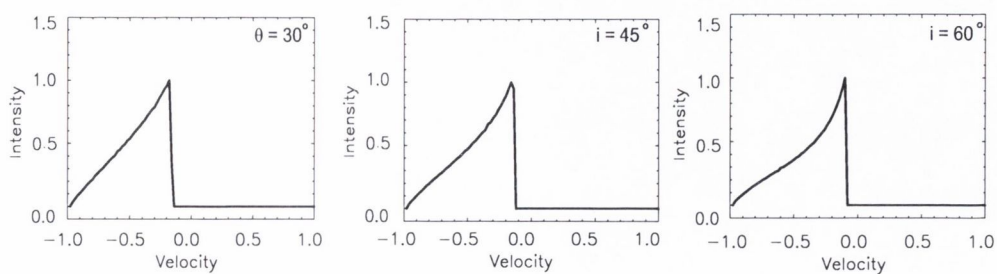


Figure A.13: Line profiles for $\theta = 30^\circ, 45^\circ, 60^\circ$ for a lateral dependent wind, $f(\theta) = (1 - 0.8 * \theta / \theta_{max})$ and $I = 0^\circ$.

say, $V_{HVC} = 285 \text{ kms}^{-1}$ and $\Delta V = 40 \text{ kms}^{-1}$. Hence a value of $\theta \approx 12^\circ$ is derived. Davis, Mundt, Eisloffel, & Ray (1995) estimate the opening angle of the L1551 IRS5 jet, to be $\sim 10^\circ$.

How well the low and high velocity components to a particular forbidden line are separated depends on the inclination I and to a smaller extent on θ . To demonstrate this point a second cone of opening angle W (where $W > \theta$) is added to the model described above. For simplicity it is assumed that the low and high velocity components do not interact. Figure A.14 illustrates how the components blend as I is increased from 0° to 90° . Clearly low and high velocity components will be indistinguishable for jets close to the plane of the sky. One example of a CTTS whose jet has a value of I close to 90° is DP Tau. Blended low velocity emission only, is detected for this source and velocities in the blue-shifted jet are low, compared to other similar sources ($\sim -60 \text{ kms}^{-1}$). This is consistent with an outflow inclined at an angle of $\sim 90^\circ$ to the line of sight (Hirth, Mundt, & Solf, 1997; Mundt & Eisloffel, 1998).

Lastly Figure A.15 shows how for a LVC of opening angle $W = 60^\circ$ and $I = 45^\circ$ the two components will merge as the opening angle of the HVC is increased from 20° to 50° . As the radial velocity of the LVC is significantly smaller than the velocity of the HVC, the width of the LVC changes relatively little with I compared to the width of the HVC. When

$$\theta \geq \arccos[V_{HVC/LVC}] - I \quad (\text{A.35})$$

the two components will start to blend. $V_{HVC/LVC}$ is the ratio of the velocities of the high and low velocity components and for the purpose of the results presented in Figure A.15, $V_{HVC/LVC} = 0.1$

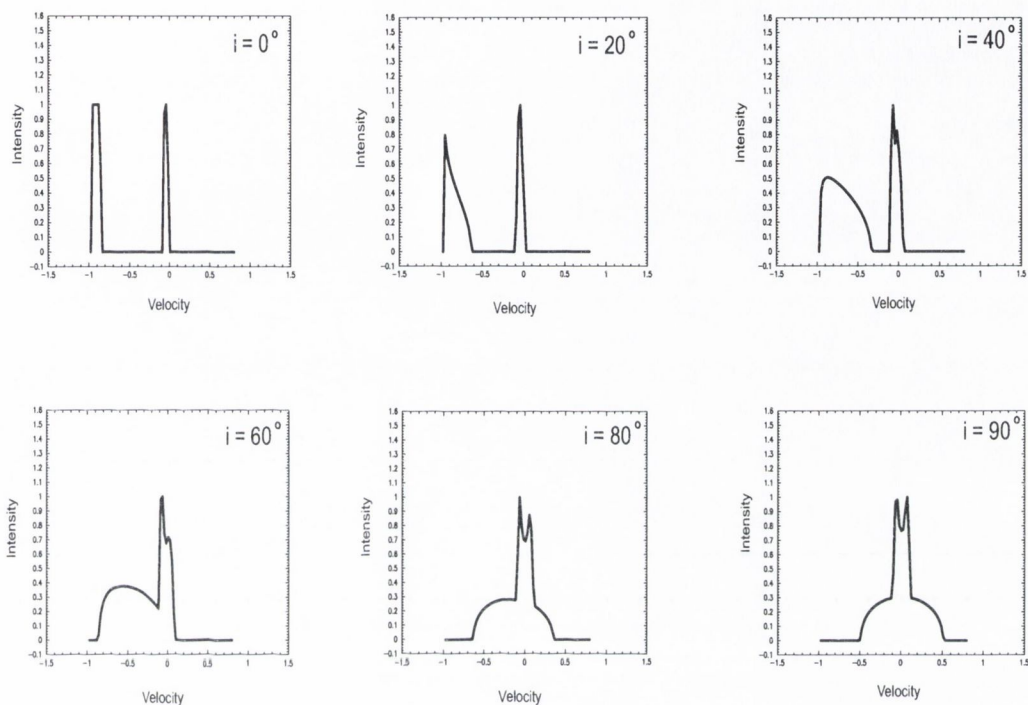


Figure A.14: Figure, illustrating the blending of low and high velocity components with increasing I . The two components become indistinguishable when the jet is close to the plane of the sky.

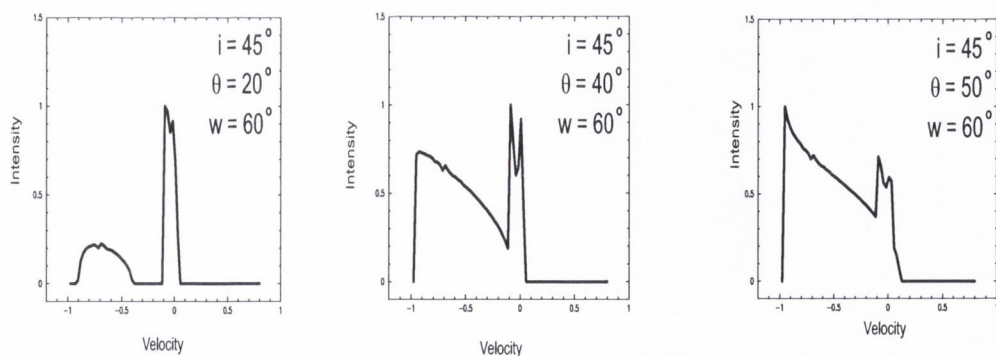


Figure A.15: Figure, illustrating the blending of low and high velocity components with increasing θ

Appendix B

Nyquist Sampling the Spatial Profile

Chapter 2 section 2.2 describes, how for a fixed seeing the spectro-astrometric accuracy is set by the number of detected photons or the S/N. However the seeing also influences the accuracy as the smaller the seeing the smaller the spectro-astrometric error. As it is an important goal that the PSF of the continuum and line emission, be well sampled spatially the pixel scale of any detector must be considered when seeking to improve the seeing. That the FWHM of any spatial profile be spread across two or more pixels, is the Nyquist sampling requirement. Table B.1 below lists all the observations that were analysed using spectro-astrometry and gives the seeing (measured from the spectrum) and pixel scale in each case.

All the infrared data (as described in Chapters 3 and 4) was taken with CGS4 on UKIRT. From Table B.1, it is clear that the detector used with CGS4 has large or “*chunky*” pixels compared to the other detectors hence there is a risk that, the PSF of a spectrum taken with this instrumental set could be under sampled. Somewhat unusually observations taken with CGS4 on UKIRT, with spectro-astrometry in mind, require poor seeing $\sim 2''$. As Mauna Kea is one of the best observing sites in the world due to the low seeing achievable it is often necessary in these cases to de-focus the telescope to compensate for a value of the seeing much less than the pixel scale. For the observations taken with CGS4 discussed here the seeing was poor enough to ensure that the continuum PSF, was nyquist sampled without the need to de-focus the telescope. The case of Pa β from V536 Aql where the PSF

Object	Emission Line	Seeing (arcsec)	Pixel scale (arcsec per pixel)
SVS13	[FeII]	1.9	0.88
IRAS04239+2436	[FeII]	2.0	0.88
L1551-IRS5	[FeII]	2.2	0.88
DG Tau	Pa β	2.0	0.88
	[FeII]	2.0	0.88
	Optical FELs	2.0	0.19
V536 Aql	Pa β	1.6	0.88
	Optical FELs	1.5	0.19
LkH α 321	Pa β	1.8	0.88
	Optical FELs	1.0	0.19
RW Aur	[FeII]	2.0	0.88
R Mon	Optical FELs	2.2	0.33
PV Cep	Optical FELs	1.0	0.33
V645 Cygni(0°)	Optical FELs	1.7	0.33
V645 Cygni(24°)	Optical FELs	1.1	0.33
V645 Cygni(80°)	Optical FELs	2.0	0.33
V645 Cygni(325°)	Optical FELs	1.0	0.33
LkH α 233(30°)	Optical FELs	4.0	0.33
LkH α 233(60°)	Optical FELs	2.2	0.33
LkH α 233(70°)	Optical FELs	2.2	0.33
LkH α 233(150°)	Optical FELs	2.6	0.33
ρ Oph 102	Optical FELs	0.65	0.182

Table B.1: Table Comparing Pixel scale and Seeing for each of the observations from which spatial information was extracted using spectro-astrometry

was slightly under-sampled is the only possible exception. Under-sampling causes the PSF to be less gaussian in shape however as the effect is very small for this observation this was not considered a problem. The S/N was high enough to achieve a sufficient accuracy and the offsets detected in the Pa β ELR were also detected in the H α and optical FELs. The optical FEL spectrum of V536 Aql was taken with the IDS on the INT and as can be seen from the table above, this spectrum was well sampled by the pixel scale.

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