Near-infrared echelle spectroscopy of Class I protostars: molecular hydrogen emission-line (MHEL) regions revealed

Christopher J. Davis,1* Thomas P. Ray,2 Louis Desroches1,3 and Colin Aspin4

1Joint Astronomy Centre, 660 North A’ohokū Place, University Park, Hilo, Hawaii 96720, USA
2Dublin Institute for Advanced Studies, School of Cosmic Physics, 5 Merrion Square, Dublin 2, Ireland
3Dept. of Physics, University of Victoria, P.O Box 3055 STN CSC, Victoria, BC V8W 3P6, Canada
4UK Gemini Science Office, Nuclear & Astrophysics Laboratory, Keble Road, Oxford OX1 3RH

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ABSTRACT

Infrared echelle spectra are used to trace dynamic activity in the immediate vicinity of Class I outflow sources. The H2 and Brγ observations presented here trace different components of these emission-line regions; indeed, they are thought to trace the orthogonal processes of outflow and infall respectively.

High-velocity H2 emission is detected in the extended lobes of nine outflows. In addition, complex H2 line emission is observed within a few hundred au of nine of the outflow sources. We refer to these H2 emission regions as ‘molecular hydrogen emission-line’ regions, or MHELs, and compare their properties to those of forbidden emission-line regions (FELs) observed in classical T Tauri and some Herbig AeBe stars. Like the FELs, both low- and high-velocity components (LVCs and HVCs) are observed in H2, with blueshifted velocities of the order of 5–20 and 50–150 km s\(^{-1}\) respectively. LVCs are more common than HVCs in MHEL regions, and like their FEL counterparts, the latter are spatially further offset from the exciting source in each case. The MHEL regions – which are in all cases preferentially blueshifted – are assumed to be associated with the base of each outflow.

Brγ profiles are detected towards four of the Class I sources observed (SVS 13, IRAS 04239+2436, HH 34-IRS and GGD 27(1)) as well as towards the T Tauri star AS 353A. These lines are all broad and symmetric, the line peaks being blueshifted by 30 km s\(^{-1}\). The profiles are typical of the permitted hydrogen line profiles observed in many T Tauri stars, and probably derive from magnetospheric accretion flows. We do not observe redshifted absorption features (inverse P-Cygni profiles) in any of the sources, however. Nor do we detect a dependence on linewidth with inclination angle of the system to the line of sight, as is predicted by such accretion models. No Brγ is detected in the extended flow lobes. Instead, the emission is confined to the source and is spatially unresolved along each flow axis.

Key words: circumstellar matter – ISM: jets and outflows – ISM: kinematics and dynamics – ISM: lines and bands – infrared: stars.

1 INTRODUCTION

High-resolution optical and near-infrared (near-IR) spectroscopy of T Tauri stars tell us much about accretion and outflow processes within a few hundred au of each source (e.g. Hartigan, Edwards & Ghandour 1995; Hirth, Mundt & Solf 1997; Muzerolle, Calvet & Hartmann 1998a; Alencar & Basri 2000; Folha & Emerson 2000). Yet there is little observational data for more deeply embedded ‘Class I’ sources, sources that are known to drive more powerful molecular outflows. This is partly a result of the difficulties associated with observing these sources, because of the increased extinction towards them. Indeed, many have not been observed directly at optical wavelengths (though see the recent spectroscopic survey of Kenyon et al. 1998).

The Balmer, Paschen and Brackett hydrogen recombination lines observed towards T Tauri stars are thought to derive from shocks associated with magnetospheric accretion (Hartmann, Hewett & Calvet 1994; Muzerolle et al. 1998a). Broad linewidths and the presence or absence of redshifted absorption features are thought to depend on the velocity field and geometry of each system. By comparison, the forbidden line emission (e.g. [S II], [O I], [N II] etc.) observed in the same or similar T Tauri stars and

*E-mail: cdavis@jach.hawaii.edu
Class II outflow sources is interpreted in terms of jets or outflows that are observed close to their driving sources (Hirth, Mundt & Solf 1994a, Hirth et al. 1994b; Hartigan et al. 1995; Corcoran & Ray 1998). These forbidden emission-line regions, or FELs, exhibit complex and/or multiple velocity components; the emission is also usually extended along the flow axis.

In this paper we focus on near-IR observations of more deeply-embedded, Class I outflow sources. From published low-resolution spectroscopic surveys, many of our targets are known to exhibit HI and H$_2$ lines in their spectra (Carr 1990; Greene & Lada 1996a; Solf 1994a, Hirth et al. 1994b; Hartigan et al. 1995; Corcoran & Aspin 1997). We discuss infrared echelle spectroscopy of nine outflow regions. The molecular hydrogen $1-0S(1)$ and H$_2$ Br$\gamma$ observations obtained trace very different excitation conditions; the H$_2$ traces dense, molecular gas of relatively low excitation ($n_{H_2} \approx 10^3$ cm$^{-3}$; $T \approx 2000$ K) while the Br$\gamma$ emission traces hot, hydrogen-recombination zones. In almost all of the regions observed, H$_2$ line emission is detected directly towards the outflow source, as well as in the more extended flow lobes. We associate the former with what we shall henceforth refer to as ‘molecular hydrogen emission-line’ (MHEL) regions. This molecular line emission region is generally confined to within a few arcsec (five to ten thousand au at the typical distances of our sources) of the outflow source. Br$\gamma$ emission is observed only towards a few of the outflow sources and is spatially unresolved along the outflow axes. We associate the H$_2$ emission with outflow activity and, akin to studies of T Tauri stars (e.g. Folha & Emerson 2000), the Br$\gamma$ with accretion.

The targets are discussed individually in Section 3. In Section 4 we consider the origins of the observed emission features in terms of published infall and outflow models, and look for correlations between H$_2$ and H$_2$ line luminosities, other outflow parameters and the ages and luminosities of the driving sources.

2 OBSERVATIONS

High-resolution, near-IR echelle spectra were obtained at the UK Infrared Telescope (UKIRT) using the cooled grating spectrometer CGS 4 (see Table 1). The instrument utilizes a 256 x 256 pixel InSb array and has a pixel scale of 0.41 x 0.90 arcsec (0.41 arcsec in the dispersion direction); with a slit 2 pixels wide, the velocity resolution was $\sim 15$ km s$^{-1}$ (although over-sampled spectra were obtained by physically shifting the array by 1/2 pixel, so that two detector positions were observed per resolution element). The instrumental profile in the dispersion direction, as measured from Gaussian fits to sky lines, was 17.7(±2.5) km s$^{-1}$ and 18.0(±1.5) km s$^{-1}$ in the H$_2$ and Br$\gamma$ spectra respectively. Spectra were obtained in both H$_2$ 1-0S(1) (at $\lambda_{\text{vac}} = 2.121833$ μm; Bragg, Smith & Brault 1982) and H$\beta$ Br$\gamma$ (at $\lambda_{\text{vac}} = 2.166167$ μm). For each target the slit orientation was set to that of the major jet or outflow axis (see Table 1), determined from images of the targets found in the literature. Object–sky–object sequences were repeated a number of times on each source to build up signal-to-noise, the sky position being typically a few arcmin away from the source. Each spectral image was bias subtracted and flat-fielded (using a blackbody source in the calibration unit) before the data were combined to produce one ‘reduced group’ spectral image per target.

The data were wavelength calibrated using sky lines (for H$_2$, four bright lines occupy the passband of the echelle at 2.122 μm; Davis et al. 2000) or a combination of sky and argon arc lines (both were needed to calibrate the Br$\gamma$ data): we used the OH calibrations of Oliva & Orligia (1992). The IRAF tasks used to accomplish this (IDENTIFY, RE-IDENTIFY, FITCOORDS and TRANSFORM) also corrects for distortion along the columns in each image (i.e. along arc or sky lines). The relative velocity calibration across each spectral image, measured from Gaussian fits to sky lines in ‘velocity-calibrated and distortion-corrected’ raw frames, is estimated to be accurate to $\pm 5$ km s$^{-1}$. Instrument flexure over the duration of the observations could, however, introduce additional 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 (Lumsden & Hoare 1999). By comparing the positions of sky lines in a number of raw frames we found that this effect was small; indeed, the narrowness of the H$_2$ emission features observed at some locations in the final, reduced data (as compared to the instrumental profile width, which is measured from just one frame), confirms this finding. Nevertheless, flexure could still result in an additional broadening of H$_2$ lines and

Table 1. Log of observations obtained.

| Source | RA$^a$ Dec$^a$ | Line | Date | Slit Angle | Total On-Source Exposure Time |
|--------|----------------|------|-------|------------|-----------------------------|
|        | (2000.0)       |      |       | (E of N)   | (s)                         |
| SVS 13 | 03 29 03.7     | H$_2$ | 19990831 | 123°       | 720                      |
| B5-IRS1 | 03 47 41.6     | H$_2$ | 19980902 | 73°         | 960                     |
| IRAS 04239+2436 | 04 26 56.4 | H$_2$ | 19980831 | 45°         | 1200                   |
| L1551-IRS5 | 04 31 33.6 | Br$\gamma$ | 19991126 | 66°         | 3600                   |
| HH 34-IRS | 05 35 29.8 | H$_2$ | 19991126 | 167°        | 4800                   |
| HH 72-IRS | 07 20 08.4 | H$_2$ | 19991125 | 90°         | 3000                   |
| GGD 27  | 18 19 12.2     | H$_2$ | 19980901 | 188°        | 1440                   |
| AS 353A | 19 20 31.0     | H$_2$ | 19991125 | 106°        | 960                    |
| HH 379-IRS | 21 45 08.2 | H$_2$ | 19990801 | 82°         | 1200                   |

Note. $^a$Position of the central driving source of the outflow.

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3 RESULTS

Echelle spectra of each outflow region were obtained in both H$_2$ 1-0S(1) and H$\upalpha$ Br$\gamma$ emission (Table 1); the slit position angles (p.a.) were set to that of each large-scale outflow, as indicated by previous published observations of each flow. H$_2$ position–velocity (P–V) diagrams are shown in Fig. 1. These show not only line emission coincident with the outflow sources, but also complex velocity structure in many of the extended outflow lobes and Herbig–Haro (HH) objects.

The Br$\gamma$ observations are shown in Fig. 2. In all regions where Br$\gamma$ was detected, the emission was confined to the outflow source itself. Gaussian fits to cuts made perpendicular to the stellar continua in each Br$\gamma$ P–V plot show that the emission is unresolved along the slit/flow axis, to within $\pm$2 arcsec of the outflow source. Consequently, we present H$\upalpha$ spectra extracted from each spectral image rather than P–V plots. For comparison, the equivalent H$_2$ spectra are also shown.

Below we discuss the results pertaining to each source separately.

3.1 SVS 13 (HH 7-11)

The HH 7-11 outflow in NGC 1333 ($d \approx 220$ pc) has been observed at near-IR wavelengths by a number of groups (e.g. Garden, Russell & Burton 1990; Carr 1993; Gredel 1996; Everett 1997; Chrysostomou et al. 2000; Davis et al. 2000). The HH features in the south-eastern, blueshifted lobe of this bipolar flow are distributed along the walls of a cavity, the leading edge of which is capped by the HH 7 bow shock. HH 7-11 is also associated with complex line emission. Recent high-resolution, interferometric millimetre-wave observations trace a toroidal dust/gas disc structure as well as the inner regions of a bipolar CO outflow cavity (which has a notably broad opening angle of almost 90º; Langer, Velusamy & Xie 1996). Both flow lobes are also traced by extensive H$_2$ emission; within 30 arcsec of the source Yu et al. (1999) observe emission in both lobes, with a bright H$_2$ peak coincident with the optical knot HH 366 E5 in the eastern, blueshifted flow.

In our echelle observations H$_2$ emission is detected towards the outflow source itself and towards HH 366 E5 in the eastern flow lobe (Fig. 1b). The latter is strongly blueshifted with a radial velocity of $-65$ km s$^{-1}$. A very faint patch of redshifted emission (at $V_{\mathrm{LSR}} \approx +50$ km s$^{-1}$), found at roughly the same distance from the source as E5, though in the western lobe, was detected at the 2–3$\sigma$ level in our data. Here the CGS 4 slit passed just north of an H$_2$ knot WSW of IRS 1. This knot is evident in the H$_2$ data of Yu et al. (1999), though it extends over almost 100 km s$^{-1}$ full width zero intensity (FWZI).

3.2 B5-IRS 1 (HH 366)

 Barnard 5 is situated at the eastern end of the Perseus cloud complex ($d \approx 350$ pc). The embedded YSO B5-IRS 1 drives an extensive east–west molecular outflow (Goldsmith, Langer & Wilson 1986; Fuller et al. 1991; Yu, Billawalla & Bally 1999) that excites two groups of HH objects, HH 366E and 366W, situated some 30 arcmin ($\sim 1$ parsec) to the east-north-east (ENE) and west-south-west (WSW) of IRS 1 (Bally, Devine & Alten 1996). Interferometric millimetre-wave observations trace a toroidal dust/gas disc structure as well as the inner regions of a bipolar CO outflow cavity (which has a notably broad opening angle of almost 90º; Langer, Velusamy & Xie 1996). Both flow lobes are also traced by extensive H$_2$ emission; within 30 arcsec of the source Yu et al. (1999) observe emission in both lobes, with a bright H$_2$ peak coincident with the optical knot HH 366 E5 in the eastern, blueshifted flow.

No Br$\gamma$ emission was detected towards B5-IRS 1 (Fig. 2). The H$_2$ profile observed towards the source is somewhat asymmetrical, exhibiting a weak blueshifted wing that extends out to at least $-40$ km s$^{-1}$. The line profile is centred at $\sim 4(\pm 5)$ km s$^{-1}$, close to the systemic velocity of $-10$ km s$^{-1}$ (Yu et al. 1999), though it extends over almost 100 km s$^{-1}$ full width zero intensity (FWZI).

3.3 IRAS 04239+2436 (HH 300)

The low-luminosity Class I protostar IRAS 04239+2436 has a rich near-IR spectrum (Greene & Lada 1996b). The source, situated in the B18 cloud in Taurus ($d \approx 140$ pc), probably excites a group of extensive optical HH bow shocks (HH 300: Reipurth, Bally & Devine 1997) found about 30 arcmin to the south-west, as well as a more compact conical HH feature just 30 arcsec to the north-east of the source. Lucas & Roche (1998) present near-IR imaging and polarimetric observations of the source and associated conical reflection nebula, which opens in a direction towards the north-eastern HH knot 300D.
Although \( \text{H}_2 \) emission was only detected close to the source, the emission peak (superimposed on the stellar continuum in Fig. 1c) is extended along the southwestern flow lobe (traced faintly in Fig. 1c at negative slit offsets). The \( \text{H}_2 \) profile in Fig. 2 is considerably narrower than the \( \text{Br}\gamma \) profile observed towards IRAS 04239+2436, the FWZI of the latter measuring \( \sim 470 \text{ km s}^{-1} \). Both lines peak within a few \( \text{km s}^{-1} \) of the systemic velocity of \( \sim 8 \text{ km s}^{-1} \), however.

### 3.4 L 1551-IRS5

The proximity of this source to the earth (\( d \sim 140 \text{ pc} \)), the well-defined bipolar CO outflow and the array of optical and near-IR shock features associated with it have attracted considerable attention from observers (e.g. Mundt & Fried 1983; Stocke et al. 1988; Moriarty-Schieven & Snell 1988; Davis et al. 1995). The south-western, blueshifted flow lobe consists of a compact collimated flow and an extensive wind-swept cavity. IRS 5 is in fact a binary system that appears to drive two jets (Fridlund & Liseau 1998; Hartigan et al. 2000), a brighter (at optical wavelengths) jet that terminates at a bow shock some 10–12 arcsec from the source, and a fainter, though more extended, jet that is traced twice as far from the source. The wind-swept cavity, on the other hand, extends over 10 arcmin (0.5 pc).

In the \( \text{H}_2 \) P–V plot in Fig. 1(d) we see line emission coincident with IRS 5 as well as in both the blue and redshifted jet lobes. In the south-western blue lobe (negative offsets in Fig. 1d) two velocity components are observed, a stationary component that is detected along the full length of the bright optical jet, and a steadily-increasing velocity component that reaches about half-way along the jet. The latter is suggestive of steady acceleration along the flow, the gas reaching a radial velocity of almost \( \sim 60 \text{ km s}^{-1} \). This is in contrast to optical kinematic studies which indicate decreasing jet velocities with distance from the source (Hartigan et al. 2000). In \( \text{H}_\alpha \), for example, the velocity of the peak of the observed emission profiles decreases from \( \sim -290 \text{ km s}^{-1} \) at the base of the bright optical jet to \( \sim -120 \text{ km s}^{-1} \) at the end of the optical jet, about 20 arcsec from the driving source (Stocke et al. 1988). This suggests a different origin for the optical and \( \text{H}_2 \) emissions; the latter could be associated with the second, slower and much fainter optical jet that runs parallel with the brighter, much faster optical jet. The Fabry–Perot observations of Hartigan et al. (2000) indicate radial velocities along the slower optical jet of about \( -60 \text{ km s}^{-1} \), similar to the velocities measured in \( \text{H}_2 \).
The $\text{H}_2$ emission along the IRS5 flow terminates in a double-peaked profile that is spatially coincident with the optical jet bow shock (labelled in Fig. 1d and discussed further in Section 4.5).

No Br$\gamma$ emission was detected towards IRS5; however, the blueshifted, high-velocity jet component is traced back towards the source, this being evident as a ‘bump’ on the blueshifted side of the otherwise Gaussian $\text{H}_2$ profile in Fig. 2. The profile peaks at...
27 km s\(^{-1}\); this value is blueshifted by \(-13\) km s\(^{-1}\) from the systemic velocity (Moriarty-Schieven & Snell 1988).

### 3.5 HH 34-IRS

The archetypal HH 34 optical jet and bow shock in L 1641 in Orion \((d \sim 450\) pc) forms part of a parsec-scale ‘superjet’ that includes HH 33, 40 and 85 to the north, and HH 86-88 in the south (Devine et al. 1997a). Overall, the flow has a total length of at least 3 pc. HH 34 itself has been the subject of intense scrutiny (e.g. Reipurth et al. 1986; Bührke, Mundt & Ray 1988; Eisloeffel & Mundt 1992; Heathcote & Reipurth 1992), yet the jet has only recently been detected in H\(_2\), the emission being relatively weak (Stanke, McCaughrean & Zinnecker 1998). HH 34 is also associated with a weak CO outflow (Chernin & Masson 1995).

Here we detect distinct H\(_2\) emission features towards HH 34-IRS and along the southern, blueshifted optical jet (Fig. 1e). The H\(_2\) in the jet coincides with optical knots C, I-J and L (Bührke et al. 1988; Ray et al. 1996), the distances of these H\(_2\) counterparts from the near-IR source position being 7.7, \(-20\) and 27.9 arcsec respectively. The H\(_2\) emission found between knots I and J is probably associated with the extended bow wings of knot J. Indeed, in this portion of the HH 34 jet knots I and J are the most laterally extended and most resemble bow shocks (see e.g. the HST images of Ray et al. 1996). Also, the H\(_2\) observed near knot L actually peaks just ahead of the optical emission and may likewise be associated with the flanks of a bow shock further downwind. Deep, near-IR imaging is required to investigate these associations further.

The HH 34 jet is known to be of low excitation (Reipurth et al. 1986). The central portion of the jet – around knot I – is brightest in [S\(\text{II}\)] emission, the optical knot brightnesses fading nearer the source and further downwind. Correspondingly, the gas excitation in the jet knots drops in this central region, as traced by the [S\(\text{II}\)]/H\(_\alpha\) ratio along the flow (Bührke et al. 1988). The detection of H\(_2\) emission in this portion of the jet is therefore not too surprising.

The H\(_2\) emission along the jet is all blueshifted out to radial velocities of \(-100\) km s\(^{-1}\). These velocities are roughly equal to those measured at optical wavelengths (though note that Bührke et al. (1988) and Heathcote & Reipurth (1992) report somewhat
different velocities for the observed jet section). The optical and H$_2$ emissions thus almost certainly derive from the same shock features in the jet.

Towards HH 34-IRS, both H$_2$ and Br$_\gamma$ emission is detected. As with the other YSOs observed, the profile of the latter is much wider than that of the former. Both lines are blueshifted with respect to the systemic velocity of $v_{lsr} = 8\pm 1$ km s$^{-1}$ (Chernin & Masson 1995); Gaussian fits to the profiles yield peak velocities of $v_1 = 13\pm 8$ and $v_2 = 24\pm 5$ km s$^{-1}$ for H$_2$ and Br$_\gamma$ respectively.

### 3.6 HH 72-IRS

HH 72 ($d \sim 1500$ pc) in L 1660 is associated with an east–west orientated bipolar molecular outflow (Schwartz, Gee & Huang 1988; Reipurth & Graham 1988). The optical HH knots are only associated with the eastern end of the flow, where it exits the dense core that harbours the powering source. Near-IR observations reveal additional shock features along the flow axis, as well as the likely driving source, HH 72-IRS (Davis et al. 1997). HH 72-IRS is situated about 25 arcsec to the east of the catalogue position of IRAS 07180-2356. However, the CO 2-1 maps of Schwartz et al. (1988), combined with unpublished higher-resolution CO observations obtained by one of us (CJD) and the near-IR observations discussed below, strongly indicate that the infrared source HH 72-IRS is the true outflow source.

Complex, high-velocity H$_2$ line emission is observed along much of the eastern, blueshifted flow lobe in HH 72. Once again, double-peaked velocity profiles are observed, this time towards the HH 72B bow shock (labelled in Fig. 1f; see also the H$_2$ image of Davis et al. 1997). Consistently high H$_2$ velocities are observed along much of the flow between the IRS source and HH 72B; shock velocities in excess of 150 km s$^{-1}$ are thus inferred, not just for the leading bow shock, but for most of the H$_2$ features along the flow axis. There is also a faint patch of marginally detected redshifted emission in the counterflow that again hints at a symmetrical bipolar flow centred on HH 72-IRS. Our east–west orientated CGS 4 slit passed just to the north of the H$_2$ emission observed in the western flow lobe (Davis et al. 1997).

No Br$_\gamma$ emission was detected in this system. However, the H$_2$ profile towards the source is somewhat unique in being highly structured (Fig. 2). At least three velocity peaks are observed, at $v_1 = 13\pm 8$, $v_2 = 40\pm 5$, and $v_3 = 24\pm 5$ km s$^{-1}$; these sit on a blue wing that extends to a velocity of $v_{lsr} = 165\pm 5$ km s$^{-1}$ (the L 1660/HH 72 systemic velocity is $v_{lsr} = 20$ km s$^{-1}$; Schwartz et al. 1988). In most of the other YSOs observed, the H$_2$ emission coincident with the outflow source is confined to low radial velocities, even when high velocities are observed further out in the flow lobes (see the plots in Fig. 2). However, in the HH 72-IRS flow H$_2$ at very high velocities is observed directly towards the source as well as in the extended flow. Of the other sources observed, only SVS 13/HH 7-11 exhibits a similarly complex, high-velocity H$_2$ profile coincident with the source.

### 3.7 GGD 27 (HH 80/81)

GGD 27 is a well-studied high-mass star forming region situated in L 291 in Sagitarius ($d \sim 1.7$ kpc). Near- and mid-IR observations reveal a number of embedded sources associated with IRAS.
18162–2048 (Aspin et al. 1991, 1994). These IR sources lie at the geometric centre of a massive CO outflow (Yamashita et al. 1989). Luminous HH objects, HH 80–81, are also observed (Heathcote, Reipurth & Raga 1998) some 4–5′ arcmin south of the source region. The flow is probably driven by a source undetected at near-IR wavelengths; designated GGD 27-ILL by Aspin et al. (1991), this mid-IR source is offset by approximately $-2.1$, $-1.5$ arcsec from the bright near-IR peak IRS 2. GGD 27-ILL is also, to within a few arcsec, coincident with a radio continuum source which drives a highly-collimated bipolar radio jet (Marti et al. 1993); this jet is orientated along the CO flow axis and points towards the distant HH objects 80/81.

For both H$_2$ and Br$\gamma$ observations of this region, the slit position was set so that it bisected the two bright near-infrared sources, IRS 1 and IRS 2. Here, for simplicity, we refer to the brighter source as GGD 27 (1) and the fainter, more northerly source, as GGD 27 (2); this latter peak likely represents nebulosity associated with the outflow driving source, GGD 27-ILL.

H$_2$ emission was detected along much of the slit (Fig. 1g). Faint, diffuse emission is observed near the near-IR reflection nebula to the north of the two stars GGD 27 (1) and (2) (offset $\sim-40$ arcsec in Fig. 1g), while much brighter knots of emission are detected towards GGD 27 (2) and in between the two stars. In all cases, the line emission peaks at precisely the systemic velocity of $12.5$ km s$^{-1}$. The H$_2$ peak situated midway between GGD 27 (1) and (2) is almost certainly associated with the collimated flow, being only a few arcseconds south of the embedded mid-IR/radio source GGD 27-ILL.

H$_2$ and Br$\gamma$ observations of the two infrared stars are shown in Fig. 2. It is interesting to note that towards the brighter source (1) only Br$\gamma$ emission is observed, whereas towards the fainter star (2) only H$_2$ emission is detected. Although the H$_2$ profile towards the latter peaks at the systemic velocity, the Br$\gamma$ profile towards the former is clearly blueshifted, peaking at $-60(\pm20)$ km s$^{-1}$; it also exhibits a distinct redshifted wing.

3.8 AS 353A (HH 32)

The classical T Tauri star AS 353A ($d \sim 300$ pc; Mundt, Stocke & Stockman 1983; Eisloffel, Solf & Böhm 1990) drives an obliquely-viewed bipolar HH flow, HH 32 (Hartigan, Mundt & Stocke 1986; Davis, Eisloffel & Smith 1996; Curiel et al. 1997) that is somewhat unusual because the redshifted lobe is much brighter than the blue lobe (discussed by Davis et al. 1996 and references there-in). Optical and near-IR images and spectroscopy of the leading HH 32 bow shock are well-modelled if the flow is inclined at $\sim30^\circ$ to the line of sight (Solf, Böhm & Raga 1986; Hartigan, Raymond & Hartmann 1987; Davis et al. 1996).

As with GGD 27, two infrared stars were observed in the AS 353A region (Fig. 1h). AS 353A itself, the source of the bipolar HH 32 outflow, is here referred to as AS 353A (1), while the fainter source situated $\sim15$ arcsec to the east of AS 353A (1) is referred to as star (2). H$_2$ emission associated with the HH 32 bow shock has been discussed by Davis et al. (1996). We will therefore only consider the line emission associated with the two stars.

We again see contrasting line emission properties in the two stars observed (Fig. 2); Br$\gamma$ is observed only in the brighter T Tauri star AS 353A (1), while H$_2$ is only detected in the fainter star (2). In both cases the line profiles are marginally blueshifted, to LSR radial velocities of $-24(\pm5)$ km s$^{-1}$ [Br$\gamma$-AS 353A(1)] and $-4(\pm5)$ km s$^{-1}$ [H$_2$-AS 353A(2)] with respect to the systemic velocity of $\sim8$ km s$^{-1}$ (Edwards & Snell 1982). Both profiles are also very symmetrical (Gaussian).

3.9 HH 379-IRS

HH 379 is situated in Cygnus near the molecular cloud 093.5-04.3 (in the catalogue of Dobashi et al. 1994) at a distance of $\sim0.9$ kpc. HH 379 may be associated with IRAS 21432+4719. The IRAS position is, however, offset by almost 1 arcmin from a compact optical nebula that probably marks the true outflow source location (Devine, Reipurth & Bally 1997b); source confusion and/or poor IRAS coordinates may account for this offset.

We assumed that the conical nebula is associated with the HH energy source and therefore positioned our spectrograph slit through the nebula orientated along the axis that links the nebula with the HH object. No continuum emission was detected from the outflow source in our high-resolution echelle data. However, faint H$_2$ line emission was observed towards the source position (Fig. 1i). The H$_2$ peak in the P–V diagram does appear to be elongated at a position angle that implies a blueshifted flow component towards the west of the source and a redshifted component to the east, although further kinematical studies of the source and more extended HH 379 outflow system are needed to confirm this. The central H$_2$ peak, plotted in Fig. 2, is, nevertheless, centred precisely at the systemic velocity of the parent cloud ($\sim3.5$ km s$^{-1}$, Dobashi et al. 1994).

4 DISCUSSION

4.1 Br$\gamma$ emission from accretion

Profiles of permitted hydrogen line emission profiles, observed towards a large number of classical T Tauri stars, have been interpreted in terms of both outflow and accretion (Calvet, Hartmann & Hewett 1992; Hartmann et al. 1994; Edwards et al. 1994; Muzerolle et al. 1998a). Reipurth, Pedrosa & Lago (1996) proposed a classification scheme for the observed line shapes, which they applied to their survey of H$\alpha$ line profile observations of 43 T Tauri stars. They found that while 25 per cent of the sources studied exhibited single-peaked, symmetric (or ‘Type I’) profiles, 54 per cent had blueshifted absorption features (P Cygni profiles) and 21 per cent had redshifted absorption features (inverse P Cygni profiles, or IPC). By comparison, a similar study by Folha & Emerson (2000) made in near-IR Pa$\beta$ and Br$\gamma$ indicates that most of these profiles were symmetric; 73 per cent of the 50 T Tauri stars observed in Br$\gamma$ exhibited symmetric Type I profiles, while 20 per cent had redshifted absorption features (IPC); in Pa$\beta$ 54 per cent were Type I and 34 per cent had IPC profiles. These differences, particularly between the optical and near-IR lines, may be caused by opacity effects.

The absorption features that define P Cygni and IPC profiles are thought to be signposts of outflow and accretion processes respectively. Redshifted absorption probably derives from accretion as the infalling gas absorbs emission from the hot accretion shock; blueshifted absorption likely arises from outflow, the cooler outflowing gas again absorbing emission from the protostar.

In their study of T Tauri stars, Folha & Emerson (2000) measured Br$\gamma$ linewidths (FWHM) that were typically 200 km s$^{-1}$, although lines with FWHM ranging from $\sim110$ to $\sim300$ km s$^{-1}$ were observed. Towards the Class I sources observed here (AS353A and SVS 13 have been observed before by Najita, Carr & Tokunaga 1996), the Br$\gamma$ profiles have similar widths. The line
peaks are typically blueshifted by a few tens of km s$^{-1}$, again like the Br$\gamma$ profiles observed by Folha & Emerson (2000). Models that include only outflow predict redshifted line peaks (e.g. Calvet et al. 1992) and in many cases broad, blueshifted absorption features. Neither is observed in our small sample of Class I sources, nor in the observations of Class II sources by Folha & Emerson (2000).

Instead, the blueshifted peaks and broad, symmetric line profiles observed compare (qualitatively at least) more favourably with magnetospheric accretion models (Hartmann et al. 1994; Muzerolle et al. 1998a). These models do, however, often produce redshifted absorption features as well as lines that are typically much narrower than are observed here and elsewhere (Najita et al. 1996; Folha & Emerson 2000). The linewidth and depth of the redshifted absorption is strongly dependent on inclination angle. A weak or low-temperature accretion shock might also explain an absence of redshifted absorption. Linewidths are predicted to increase, and the red absorption become more prominent, at large inclination angles (measured with respect to the line of sight; Muzerolle et al. 1998a). For the few sources observed here, for which Br$\gamma$ was detected, the flow inclination angle is reasonably well known (listed later in Table 3). Yet we do not observe any evidence of changing Br$\gamma$ line shapes with flow inclination angle; if we take AS 353A, SSV 13 and HH 34 as examples of ‘pole-on’ (small inclination angle), intermediate, and ‘disc-on’ systems respectively, we find that the linewidths are roughly the same (the HH 34-IRS profile being about 20 per cent wider), and we see no evidence of redshifted absorption, even in the Br$\gamma$ profile observed towards HH 34-IRS (although admittedly this line is relatively weak). As was noted by Folha & Emerson (2000), redshifted absorption is more typically observed in hydrogen Balmer lines than Brackett lines [for example, the H$\alpha$--H$\beta$ Balmer lines observed towards AS 353A by Alencar & Basri (2000) do have strong red absorption; the Br$\gamma$ line observed here (and by Najita et al. 1996) does not]. The lower-energy Balmer lines may thus be considered as a better probe of accretion processes, even though extinction affects are more of a problem. When considering model predictions for linewidths, one should also note that the accretion models of Hartmann, Muzerolle and co-workers do not include rotation, outflow or turbulence, process that will almost certainly broaden the theoretical line profiles and, in the case of turbulence, serve to produce more symmetric profiles (Edwards et al. 1994).

From low-resolution spectroscopic observations of 30 T Tauri stars, Muzerolle, Hartmann & Calvet (1998b) also find a very convincing correlation between Br$\gamma$ line luminosity and accretion luminosity, the latter being derived independently from the infrared-excess continuum emission. They find that the line strength decreases with decreasing accretion rate. The Br$\gamma$ luminosities measured for the five sources observed in this paper (see Table 4 below) are typical of those observed for T Tauri stars. If we assume that the Br$\gamma$ line luminosity versus accretion luminosity relationship applies also to Class I sources, then following Muzerolle et al. (1998b) we predict accretion luminosities in the range 0.2–8 L$\odot$ (the limiting sources in this range being IRAS 04239+2436 and SSV 13). There is, however, considerable uncertainty in the measured line luminosity because of the large extinctions towards the embedded, Class I sources (listed in Table 3 below). If we assume a ‘typical’ extinction of A$g \sim$ 20, then the true line luminosity would increase by a factor of 10$^{A_g/2.5}$ $\sim$ 6.3, where the extinction at 2.2 $\mu$m, A$g$ $\sim$ A$g$/10. The accretion luminosity would then be in the range $\sim$2–80 L$\odot$ for the low-mass Class I sources observed [and $\sim$3 x 10$^4$ L$\odot$ for the distant, high mass source GGD27-IRS(1)]. This very crude analysis suggests that the accretion luminosity is roughly comparable to the bolometric luminosity of each source (see Table 4).

4.2 H$_2$ emission from outflow

There are a number of distinct differences between the H$_2$ and Br$\gamma$ observations presented in this paper. The Br$\gamma$ profiles in Fig. 2 are much wider than their H$_2$ counterparts, although the H$_2$ profiles are, in a few cases at least, more structured (less Gaussian). Also, in all cases the Br$\gamma$ emission is confined to the outflow source, being unresolved along the slit/outflow direction, whereas the H$_2$ emission is extended along the flow axis, even towards sources where H$_2$ is detected only towards the source position (e.g. HH 379-IRS). To better illustrate these extended MHEL regions we plot in Fig. 3 contour diagrams of five outflow source regions. The continuum emission associated with each YSO has been fitted and removed, row-by-row via linear least-squares fits to the emission on either side of the H$_2$ line emission peaks, so that only the emission associated with the MHEL regions remains. Multiple velocity components are revealed in the MHEL regions associated with four of the five YSOs considered.

The continuum-subtracted P–V diagram for SSV 13 is dominated by two velocity peaks, a low-velocity component (LVC) at V$_{LSR}$ $\sim$ −20 km s$^{-1}$ and a high-velocity component (HVC) at V$_{LSR}$ $\sim$ −90 km s$^{-1}$. Both components have faint extensions (with positive offsets in Fig. 3; labelled 1 and 2) along the blueshifted HH 7–11 outflow lobe; the LVC also has two shorter, though brighter, extensions in the ‘counter-flow direction’ (negative offsets in Fig. 3; labelled 3 and 4), one at near-stationary velocities and the other approaching −50 km s$^{-1}$. All four features could be from the same wide-angled, blueshifted HH 7–11 flow lobe, features 3 and 4 deriving from the near-side of the flow cavity that is seen projected ‘behind’ the SSV 13 source. The outflow clearly has a wide opening angle on large scales – the HH objects 7–11 themselves represent shock nebulae along the walls of a conical cavity seen in deep optical images (e.g. Davis et al. 1995) – and the flow is inclined at a reasonably oblique inclination angle of $\sim$40$^\circ$ to the line of sight (Carr 1990).

The IRAS 04239+2436 MHEL region comprises only a single LVC, although this component extends into both the blueshifted (decreasing offsets in Fig. 3) and redshifted outflow lobes. The blueshifted extension comprises two ‘jet’ components (labelled in Fig. 3), a near-stationary cusp and a higher-velocity extension that is indicative of acceleration. The same pattern of emission features is observed in the LVC associated with the L 1551-IRS5 MHEL region; again both blueshifted (decreasing offsets in Fig. 3) and redshifted extensions are detected. Like IRAS 04239+2436, the blue MHEL lobe in L 1551-IRS5 comprises a near-stationary component and an increasing-velocity feature; both jet components in L 1551-IRS5 extend out towards the known jet bow-shock (also labelled in Fig. 3). The near-stationary and ‘accelerating’ MHEL components in the blue outflow lobes in both IRAS 04239+2436 and L 1551-IRS5 could be associated with two separate jets (as already mentioned, optical imaging of L 1551-IRS 5 indicates the possible presence of two jet flows; Fridlund & Liseau 1998) or they could represent emission from entrained gas in the walls of a single jet; the two MHEL extensions would then represent emission from the near and far sides of a ‘hollow’ H$_2$ component in each flow, the former being inclined towards the observer and the latter almost parallel with the plane of the sky.

Subtraction of the stellar continuum emission associated with
Figure 3. $H_2$ position–velocity diagrams for five of the outflow regions; only the emission near to each source is shown. In the left hand panel the continuum emission from the central source has been fitted and removed, leaving only line emission associated with the MHEL regions.

Figure 4. Measured offsets of the MHEL features observed towards four of the YSOs. MHEL points are marked with open squares (with error bars); measurements of the continuum position either side of the MHEL are marked with points. Offsets are measured in the same sense as those in Figs 1 and 3; i.e. positive offsets increase (a) for SVS 13 to the south-east, (b) for IRAS 04239+2436 to the north-east, (c) for L 1551-IRS5 to the north-east and (d) for HH 72-IRS to the east.
the HH 34-IRS MHEL region reveals only a single, relatively featureless LVC (Fig. 3) that is blueshifted by about 10 km s$^{-1}$ from the systemic velocity. In stark contrast, the HH 72-IRS MHEL region exhibits very complex velocity structure. This is probably caused in part by the greater distance to this intermediate-mass outflow source. As a consequence, the HH 72-IRS MHEL will be less well resolved from the rest of the bipolar, molecular outflow than in the other sources in Fig. 3. We do nevertheless identify two LVC components, at low- and intermediate-blueshifted velocities, and a HVC at $V_{LSR} \sim -130$ km s$^{-1}$.

It seems unlikely that molecular hydrogen would survive in the high-temperature shocks associated with the magnetospheric accretion processes discussed in Section 4.1. The fact that the $H_2$ emission regions are extended suggests that they originate in a wind rather than an accretion zone. Indeed, the MHEL regions are in many respects similar to the forbidden emission-line (FEL) regions observed in many classical T Tauri stars (Hamann 1994; Hartigan et al. 1995; Hirth et al. 1997) and some Herbig Ae/Be stars (Corcoran & Ray 1998). Spectroscopy of these optical emission-line regions reveal in many cases multiple velocity components, much like those seen here in $H_2$ towards the Class I emission-line regions reveal in many cases multiple velocity regions observed in many classical T Tauri stars (Hamann 1994; Hartigan et al. 1995; Hirth et al. 1997) and some Herbig Ae/Be stars (Corcoran & Ray 1998). Spectroscopy of these optical emission-line regions reveal in many cases multiple velocity components, much like those seen here in $H_2$ towards the Class I sources. Typically, both LVC and HVC, with velocities in the ranges $-5$ to $-20$ km s$^{-1}$ and $-50$ to $-150$ km s$^{-1}$, are observed in the FELs; similar components are observed in at least two of our Class I YSOs. The optical FELs are preferentially blueshifted, again like the MHEL regions. The optical LVC is also often spatially more compact than the HVC; the same trend is observed in two of our MHEL regions (SVS 13 and HH 72-IRS), and in a third (L1551-IRS5) the extent and offset of the LVC increases with velocity. To illustrate this last point more clearly we plot the offset of the LVC and HVC components from the YSO continuum centroid in Fig. 4.

Gaussian fits to the MHEL emission peaks and continuum strips either side of the $H_2$ emission regions were made using the P–V plots in Fig. 3. These fits yield the spatial offsets of the MHEL components from the continuum position (note that there was no measurable offset of the LVC in HH 34-IRS from the continuum position); a second-order polynomial fit to the continuum points is drawn in each plot. The scatter of the continuum position measurements about this ‘stellar centroid’ fit is of course dependent on the brightness of the observed continuum. Nevertheless, in all four cases in Fig. 4, clear offsets of the MHEL emission from the driving YSOs are apparent. The separate LVCs and HVCs in the SVS 13 and HH 72-IRS MHEL regions are represented by individual clusters of measurements: note in particular how the HVCs in these two sources are situated further from their sources than the LVCs, and in L 1551-IRS 5 and IRAS 04239+2436 how the MHEL is offset further from the source at increasing blueshifted velocities.

### 4.3 The origin of the MHEL regions

A number of theories have been presented to explain the FEL regions observed in TTs. Here we compare some of these models with our $H_2$ observations.

Models which interpret the HVC and LVC emission as being from the near and far sides of a hollow flow, observed in projection along the line of sight, seem to be ruled out. Observations clearly show that FEL line ratios in the HVCs and LVCs of the same flows differ, indicating contrasting excitation conditions in the two flow components (Hamann 1994; Hartigan et al. 1995); this is in contrast to what one would expect from the two sides of a single, hollow flow. Indeed, line ratios suggest higher densities though lower excitation in LVCs as compared to the HVCs in FEL regions. This is consistent with the LVCs being observed more often in $H_2$ than the HVCs in our (limited) sample of Class I MHEL regions. Of course, measurements of the $H_2$ excitation in the HVCs and LVCs observed in the Class I flows would be of considerable interest in similarly ruling out such a model for the MHEL regions.

Ouyed & Pudritz (1994) model FELs with a conical shock in a disc wind; they reproduce [O I] and [S II] line profiles in the hot, post-shock gas just above the disc plane. The shock serves to recollimate the magnetohydrodynamic disc wind. The model does produce complex and double peaked profiles similar to the FEL observations. The post-shock emission zone is also offset from the outflow source, though only by about $10^{11}$ cm, and again in the axially-symmetric case one would expect to see the same excitation conditions in the low- and high-velocity post-shock components, if these correspond to the LVCs and HVCs observed. Thus, such a model could at best only explain one flow component.

A model that assumes two independent flow components is preferred for the FELs (e.g. Hirth et al. 1997), and we have (as yet) no reason to believe that such a model would not also apply to the MHEL regions. Kwan & Tademaru (1988) and later Kwan (1997) suggest that while the HVC derives from a collimated, high-velocity jet, the LVC could be produced in a warm disc corona or a slow disc wind. Kwan & Tademaru (1995) model [O I] profiles for an LVC produced in a disc corona; the velocity profile extends for a few km s$^{-1}$ out to $\sim 100$ km s$^{-1}$, with the peak only slightly blueshifted from the stellar rest velocity. Their model corona, with densities of the order of $10^7$ cm$^{-3}$ and temperatures of about $10^4$ K (needed to reproduce the observed [O I] line ratios) would be conducive to $H_2$ excitation. However, the corona probably only extends to a height of about $10^{11}$–$10^{12}$ cm above the disc surface, whereas the observed LVC MHEL emission regions in SVS 13 and L 1551-IRS 5 are offset by $\sim 10^{15}$ cm from their sources (Fig. 4), with the more distant HH 72-IRS MHEL emission being offset by about $10^{16}$ cm. Thus, such coronal $H_2$ emission would have to be incorporated into the flow to distance it from the exciting source in each case.

The line profile widths displayed in Fig. 2 could be broadened by either Keplerian rotation in or near the accretion disc surface (Hartigan et al. 1995), or simply through lateral expansion of the outflowing gas (Hamann 1994). If the former applies, then the FWZI of each H2 profile should reflect the maximum velocity attained in the inner regions of the accretion disc (illustrated in Fig. 5). Given the inclination angle of the flow to the line of sight, $\theta$, one may then estimate the maximum Keplerian velocity associated with the H2 and Brγ emission regions, as $V_{\text{kep}} = \Delta V_{\text{FWZI}}/(2 \sin \theta)$; $\theta$ is the flow inclination angle to the line of sight and $\Delta V_{\text{FWZI}} = V_{\text{max(red)}} - V_{\text{max(blue)}}.$ Estimates for each source are listed in Table 2. The narrow H2 profiles obviously lead to a much lower velocity than the Brγ observations. As the square of $V_{\text{kep}}$ is inversely related to the radial distance of the emitting ‘ring’, it is not surprising that the higher-excitation Brγ emission would derive from much closer in to the star. Indeed, for a 1-M$\odot$ star, a typical broadened Brγ profile with $V_{\text{kep}} \sim 250$ km s$^{-1}$ could originate from a ring of radius $\sim 2 \times 10^{13}$ cm; the H2 would then derive from further out in the disc plane, at a radius of $\sim 9 \times 10^{12}$ cm for a keplerian velocity of 40 km s$^{-1}$ (Kwan & Tademaru 1995).

As we have established that the MHEL regions are associated with the outflow, the $H_2$ profiles could instead be broadened by expansion of the flow lobe. Taking into account the inclination...
angle of the flow axis with respect to the line of sight, $\theta$, the flow opening angle, $\alpha = 2 \arctan(\Delta V_{\text{FWZI}} \cos \theta / 2 V_{\text{peak}})$, where $V_{\text{peak}}$ is the velocity of the HVC or LVC emission peak. For ‘typical’ values of $\Delta V_{\text{FWZI}} \sim 70$ km s$^{-1}$ and $\theta \sim 45^\circ$, the full opening angle of an LVC with $V_{\text{peak}} \sim 20$ km s$^{-1}$ would be roughly 100$^2$; by comparison, an HVC with a similar FWZI though a $V_{\text{peak}} \sim 70$ km s$^{-1}$ would have an opening angle of the order of 40$^\circ$. These values are likely to be overestimated, because turbulence and thermal motions will contribute to the line broadening, even in the case of a magnetic C-shock where the excited H$_2$ molecules predominantly radiate from a region just ahead of the shock front. The observations, particularly of SVS 13 where both LVC and HVC components are clearly detected in H$_2$, do in any case show that the HVC is probably more highly collimated than the LVC, as is the case with optical FEL regions.

From our flux-calibrated spectra (Fig. 2) we may also estimate the mass of hot H$_2$ gas associated with each MHEL LVC, and subsequently the mass outflow rate specific to the H$_2$ flow component observed. The H$_2$ and Br$\gamma$ spectra plotted represent the average of three rows (centred on the source) extracted from each spectral image, and therefore cover an area of $0.8 \times 2.7$ arcsec across each source, the major axis being aligned with the flow axis. The column of H$_2$ molecules populating the $v = 1, J = 3$ ro-vibrational level is directly related to the observed flux (assuming optically thin emission) via the equation $N_{1\,3} = 4n_{\text{H}_2} (h/\pi r_{1-0}) A_{1-0}$, where $I_{1-0}$ is measured in W m$^{-2}$ sr$^{-1}$, and $v_{1-0}$ and $A_{1-0}$ are the frequency of the transition and the Einstein A coefficient respectively. With the H$_2$ molecules in local thermodynamic equilibrium, the total column of H$_2$ molecules is then given by $N_{\text{H}_2} = N_{1\,3} Z(T)/(g_{1\,3} \exp[-h r_{1-0}/kT])$, where the partition function, $Z(T)$, is related to the gas excitation temperature, $T$, by $Z(T) = 0.0247T/(1 - \exp[-6000/T])$ (Smith & Mac Low 1997). For the $1 - 0$S(1) transition observed, $A_{1-0 \, \text{S}(1)} = 3.47 \times 10^{-7}$ s$^{-1}$ and the statistical weight, $g_{1\,3} = g_3 (2J + 1) = 21$ (for an ortho-para-H$_2$ ratio of 3). H$_2$ column density estimates for the sources where emission was detected are listed in Table 3. We assume a temperature of 2000 K in the hot, post-shock gas; this is equivalent to the excitation temperatures typically observed in HH objects (e.g. Gredel 1996). The flux measurements are also corrected for extinction; although in some cases the $A_v$ estimates used may be slightly greater than the true extinction to the MHEL regions. Observed masses are given in Table 3; these are likely to be accurate to within a factor of a few, the greatest source of error being from the distance to the source used (accurate to perhaps 30 per cent) and our assumptions concerning LTE and the H$_2$ level populations. Moreover, our 0.8-arcsec wide CSG 4 slit may not include all of the H$_2$ emission region.

To calculate the mass outflow rate in each region we take the peak H$_2$ velocity observed in Fig. 2 and correct this for the flow inclination angle (if known). In a few cases, the H$_2$ profile peaks at approximately the systemic velocity. For the purpose of this analysis, we then use an arbitrary velocity of 5 km s$^{-1}$. We arrive at the values given in Table 3. Not surprisingly, the higher mass-loss rates are attributed to the more massive (and more distant) sources, GGD 27-IRS and HH 72-IRS. The quoted mass loss rates compare favourably with typical values for Class I YSOs ($\sim 10^{-7} - 10^{-8}$ M$_\odot$ yr$^{-1}$), derived for example from CO observations of molecular flows from low-mass sources (Bontemps et al. 1996). However, one should remember that we do not know the relationship between the observed hot H$_2$ component and the rest of the flow.

### 4.4 Line emission versus source and outflow parameters

Is there a correlation between the presence or absence of an MHEL or Br$\gamma$ emission region and the source age, luminosity, or any of the known outflow parameters? If, for example, the Br$\gamma$ emission derives from an accretion zone in the inner disc and the H$_2$ emission derives from the base of a large-scale molecular outflow, one would expect extinction and the inclination angle of the source to affect the observed H$_2$ and/or Br$\gamma$ line strengths. Moreover, one might assume that high-mass YSOs would produce more luminous MHEL or Br$\gamma$ emission regions, or higher-velocity components. We have investigated these possibilities in some detail and list in Tables 3 and 4 various parameters for each outflow region.

All HH sources observed possess a rising spectral energy distribution through the far-IR bands observed by IRAS and thus are considered Class I or borderline Class I/II YSOs. Source confusion is likely to affect IRAS flux measurements, however, particularly in busy star forming regions like SVS 13 and GGD 27, where multiple mid-IR and/or radio sources have been detected.

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**Table 2. Maximum Keplerian velocities, derived from the H$_2$ and Br$\gamma$ spectra separately.**

| Source          | $\Delta V_{\text{FWZI}}$ (H$_2$) (km s$^{-1}$) | $V_{\text{kep}}$ (H$_2$) (km s$^{-1}$) | $\Delta V_{\text{FWZI}}$ (Br$\gamma$) (km s$^{-1}$) | $V_{\text{kep}}$ (Br$\gamma$) (km s$^{-1}$) |
|-----------------|---------------------------------|----------------------------------|---------------------------------|----------------------------------|
| SVS 13$^1$      | 165                             | 129                              | 420                             | 327                              |
| B5-IRS1         | 69                              | 35                               | 435                             | 218                              |
| IRAS 04239+2436 | 90                              | 45                               | 45                              | 21                               |
| L1551-IRS5      | 91                              | 64                               | 383                             | 211                              |
| HH 34-IRS       | 70                              | 39                               | 393                             | 21                               |
| HH 72-IRS$^1$   | 202                             | 143                              | 505                             | 253                              |
| GGD 27 (1)      | –                               | –                                | 505                             | 253                              |
| GGD 27 (2)      | 63                              | 34                               | –                               | –                                |
| AS 353A (1)     | –                               | –                                | 647                             | 864                              |
| AS 353A (2)     | 65                              | 33                               | –                               | –                                |
| HH 379-IRS      | 45                              | 22                               | –                               | –                                |

*Note. $^1$The $\Delta V_{\text{FWZI}}$ measurements for these two sources include all of the H$_2$ emission (i.e. LVCs and HVCs; see Fig. 2).*
Table 4. Comparison of YSO characteristics, including H2 and Brγ line luminosities.

| Source       | $L_{bol}$ ($L_\odot$) | YSO Class | Refs | $L_{H_2}$ ($10^{-12}L_\odot$) | $L_{Br\gamma}$ ($10^{-10}L_\odot$) | $L_{Br\gamma}/L_{H_2}$ | $L_{bol}/L_{Br\gamma}$ |
|--------------|------------------------|-----------|------|-----------------------------|---------------------------------|---------------------|--------------------|
| SVS 13       | 50–80                  | I/II      | 1,2  | 1.2                         | 5.5                             | 15                  | 2.7                |
| B5-IRS1      | 9.6                    | I         | 1,4  | 1.8                         | <0.08                           | 4                   | 1.8                |
| IRAS 04239+2436 | 1.1–1.3               | I        | 1,2  | 3.5                         | 0.1                             | 0.9                 | 9.0                |
| L1551-IRS5   | 21–33                  | I/II      | 1,3  | 12.3                        | 1.3                             | <0.01               | 4.4                |
| HH 34-IRS    | 28–45                  | I/II      | 1,2  | 2.7                         | 1.2                             | 5.7                 | 4.8                |
| HH 72-IRS    | 170–280                | I/II      | 1,2  | 2.8                         | 65                              | <0.01               | 3.5–5.7            |
| GGD 27 (1)   | 2.6 × 10^{17}          | I/II      | 1,2  | 2.7                         | 1720                            | >72                 | 0.016              |
| GGD 27 (2)   | 1.2–1.6 × 10^{4}       | I        | 1,2  | 23                          | <0.01                           | 3.5–5.7             |
| AS 353A (1)  | 3–6                    | II       | 1,2  | 2.7                         | 4.7                             | >67                 | 4.0–8.0            |
| AS 353A (2)  | –                      | II       | 1,2  | 0.3                         | <0.09                           | –                   | –                  |
| HH 379-IRS   | 16                     | I/II      | 1,2  | 2.6                         | <0.01                           | –                   | –                  |

Notes. $^a$References to bolometric luminosity and/or YSO classification (see also the discussion in the text): 1. Chandler & Richer (2000); 2. Reipurth et al. (1993); 3. Saraceno et al. (1996); 4. Beichman et al. (1984); 5. Kenyon, Calvet & Hartmann (1993); 6. Chen et al. (1995); 7. Cohen & Schwartz (1987); 8. Cohen (1990); 9. Reipurth & Aspin (1997). $^b$Line luminosities based on distances quoted in the text and in Table 3. $^c$Ratio of bolometric luminosity to that measured at 1.3 mm, from Reipurth et al. (1993).
more distant high-mass flows may account for the decline in the 
Br/\H2 ratio that we very tentatively identify in Fig. 6.

4.5 Echelle spectroscopy of molecular bow shocks

Although the focus of this paper has been on line emission from the 
vicinity of outflow sources (the MHEL regions), we have at the 
same time observed \H2 bow shocks in the more extended flow 
lobes. Double-peaked profiles are observed in three notable bows; 
in HH 7 (offset 70 arcsec in Fig. 1a), in the L 1551-IRS5 jet bow 
about 12 arcsec to the southwest of IRS5 (negative offsets in 
Fig. 1d), and in the main HH/H2 bow HH 72B situated about 25 
arcs to the east of HH 72-IRS (positive offsets in Fig. 1f). In all 
three sources the bows are blueshifted with respect to the driving 
source.

The double-peaked velocity profiles observed in each source are 
expected of hollow, shell-like bow shocks (e.g. Carr 1993; Davis 
& Smith 1996a,b). In all three cases the low-velocity component 
is brighter than the high-velocity peak; this is consistent with a high-
velocity ‘bullet’ interpretation, rather than a ‘shocked stationary 
clump’ model (e.g. Hartigan et al. 1987).

In HH 7 the velocity separation between the low- and high-
velocity peaks is of the order of 70 km s\(^{-1}\): in the HH 72 and IRS 5 
bow shocks, the peak-to-peak separation is considerably larger, 
approaching 150 km s\(^{-1}\). The full extent of these \H2 profiles 
therefore indicates a shock velocity of the order of 100–150 km s\(^{-1}\) 
(Hartigan et al. 1987); the emission is also testament to the survival 
of \H2 in the hot, post-shock gas. Molecular hydrogen is dissociated 
in planar ‘jump’ shocks with velocities exceeding 30–50 km s\(^{-1}\) 
(Smith 1994) provided the gas density is reasonably high (this is 
expected given the strong/detectable line emission). However, the 
curved geometry of a bow, when combined with jet variability (in 
direction and velocity) can result in peak-to-peak velocity 
separations of this order for medium-to-high-velocity 
(\sim 100–200 km s\(^{-1}\)) bows orientated out of the plane of the sky 
(Downes 1996; Volker et al. 1999; Tedds, Brand & Burton 1999).

Note from Table 3 that the observed orientation of each flow is 
approximately 45°, the possible exception being HH 72 for which 
the flow orientation is not well known. If magnetic fields play a 
role, resulting in a ‘continuous’ or C-type shock, the low-velocity 
emission would then be excited in the slow or near-stationary gas 
just ahead of the shock front. Some or all of the higher-velocity 
component could also derive from the jet or Mach disc (i.e. the jet 
shock that separates the shock working surface from the jet itself).
The application of existing numerical models (see e.g. Volker et al. 
1999; Downes & Ray 1999) to give position–velocity diagrams 
like those discussed here (in particular for different viewing angles) 
would be of considerable interest.

Collectively, these echelle observations of the \H2 emission in 
the extended outflows offer further proof of the propensity of 
molecular bow shocks in outflows from embedded YSOs. Shock 
speeds associated with these bows are high, exceeding in many 
cases the \H2 dissociation speed limit [see also the high \H2 proper 
motions measured in HH 7-11 (and other sources) by Chrysostomou et al. 2000]. Flow variability and shock geometry are probably the dominant mechanisms that allow the \H2 molecules to survive at high speeds. The velocity-separation 
between peaks in the double-peaked profiles observed, measuring 
80–150 km s\(^{-1}\), nevertheless remain a challenge for those 
modelling molecular bow shocks in YSO outflows.

5 SUMMARY AND CONCLUSIONS

High-resolution echelle spectra of embedded, Class I outflow 
sources reveal H1 and \H2 line emission regions coincident with 
many of the young stellar objects (YSOs) observed. \Bry emission 
is detected towards 45 per cent of our target list; \H2 emission is 
observed towards 80 per cent of the YSOs. The \Bry emission 
is only observed coincident with the protostars, the emission being 
spatially unresolved along the slit/flow axis. Conversely, the \H2 
towards each YSO is marginally extended along the flow axis (over 
a few hundred to a few thousand AU). Spatially and kinematically 
independent \H2 features are also observed in the more distant 
molecular outflow lobes and known HH objects in most flows.

Towards YSOs where both \H2 and \Bry emission lines have been 
observed, the latter are always considerably broader than the 
former. \Bry profiles typically measure \sim 200 km s\(^{-1}\) FWZI; the 
width of \H2 profiles are of the order of 70–200 km s\(^{-1}\) FWZI, 
although the \H2 profiles do in some cases comprise of multiple 
velocity components.

The \H2 and \Bry emissions probably trace the orthogonal 
processes of outflow and infall. The characteristics of the \Bry 
profiles are similar to those observed in the more evolved T Tauri 
stars, so we attribute this emission to magnetospheric accretion 
processes. Conversely, the \H2 emission regions are comparable to 
the forbidden emission line (FEL) regions observed in classical T 
Tauri and some Herbig Ae/Be stars. We refer to the observed \H2 
regions – defined as the emission zones within a few arcsec of each 
outflow source – as molecular hydrogen emission-line region, 
or ‘MHEL’, regions. Like their optical FEL counterparts, the 
MHEL regions are preferentially blueshifted: the \H2 emission is 
generally offset from the stellar centroid by a few tenths of an 
arcs (a few hundred au in each case). In a few targets two or 
more velocity components are observed; the high velocity \H2 is 
spatially offset further from the source than the lower-velocity \H2, 
as is also the case in some FEL regions. Lastly, like FELs, MHEL 
regions seem to be a feature of both low and high-mass protostars, 
since MHELS are observed towards the distant, luminous outflow 
sources in GGD27 and HH72, as well as the low-luminosity, and 
considerably closer YSOs IRAS 04239+2436, BS-IRS1, 
L 1551-IRS 5 and HH 34-IRS.

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Figure 6. Plot of the \Bry/H2 line luminosity ratio against the bolometric 
luminosity, \Lbol (units: L\odot) for each source.
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