An unbiased search for the signatures of protostars in the ρ Ophiuchi A molecular cloud^{*,**}

I. Near-infrared observations

T. Khanzadyan¹, R. Gredel¹, M. D. Smith², and T. Stanke³

¹ Max-Planck Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
e-mail: khtig@mpia-hd.mpg.de; gredel@caha.es

² Armagh Observatory, Armagh BT61 9DG, Northern Ireland, UK
e-mail: mds@arm.ac.uk

³ MPI für Radioastronomie, Auf dem Hügel 69, 53121, Bonn, Germany
e-mail: tstanke@mpi-fr-bonn.mpg.de

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Abstract. We present an unbiased search for molecular hydrogen emission in the L1688 cloud within the ρ Ophiuchi molecular cloud complex. Our near-infrared survey covers a connected region of extent $35' \times 35'$. We detect several new H_2 flows but the total number of detected outflows is low and is consistent with the paucity of Class 0 and Class I sources in the molecular cloud. From the spatial distribution, their collimation and the individual shapes of the bow shocks, we suggest possible candidates for the outflow sources. Most of the candidate driving sources are deeply embedded in dense cores of the molecular cloud. A very young outflow arises from the newly discovered Class 0 source MMS 126. Two major outflows in the NE–SW direction arise from the YLW 15 and YLW 16 Class I sources. Three additional outflows, which both extend over several arcminutes, arise from the Class I sources YLW 31 and YLW 52. Flow directions are generally NE–SW, perpendicular to the elongation directions of the cloud filaments. The apparent extents of molecular flows are related to either the widths of cloud filaments or to the separation between filaments. The estimated jet power needed to continuously drive and excite the detected portions of the shocked H_2 outflows lies in the range 0.02 – $0.2 L_\odot$. Given the critical dependence on the environment, however, the total sizes and powers of the outflows may be considerably larger.

Key words. stars: formation – ISM: jets and outflows – ISM: clouds

1. Introduction

The ρ Ophiuchi molecular cloud complex is one of the nearest active star forming regions (see Reipurth et al. 1991; Lada et al. 1993, for reviews). The cloud complex contains a number of distinct dark clouds (Lynds 1962) with a total mass estimated to be $10^4 M_\odot$ (de Geus et al. 1990). The filamentary and clumpy distribution of the molecular gas has been revealed through large-scale CO surveys (de Geus et al. 1990; Loren 1989a,b). Embedded in the filaments are dense clumps, recognised by mapping in emission lines of NH_3 , DCO^+ and $C^{18}O$, with properties similar to the cores in Taurus (Myers & Benson 1983; Benson & Myers 1989; Loren et al. 1990; Tachihara et al. 2000). Typically, clump masses are in the range 10 – $30 M_\odot$.

In turn, these clumps contain fragments termed cores of mass $0.10 M_\odot$ – $10 M_\odot$, some of which already contain protostars and young stars (Motte et al. 1998; Johnstone et al. 2000; Stanke et al. 2004).

It is believed that star formation has been triggered by ionisation fronts and winds from the Upper Scorpius–Centaurus OB association which is located to the west of the ρ Oph region (e.g., Loren 1989a; de Geus et al. 1990). The most active part of the ρ Oph molecular cloud complex is L1688. It harbours a remarkably dense and compact population of young stellar objects with >50 stars pc^{-2} at different evolutionary stages. The vast majority of these are relatively old T Tauri stars (Class I and II) although there are a few so-called protostars (Class 0 and I) amongst them (Wilking et al. 1989; Barsony et al. 1997; Bontemps et al. 2001). The population of young stars has been studied across the spectrum: in the radio (Andre et al. 1987; Leous et al. 1991; Mezger et al. 1992; Bontemps et al. 1996), the millimetre (Andre et al. 1990), the infrared (e.g., Barsony et al. 1997; Luhman & Rieke 1999; Bontemps et al. 2001; Allen et al. 2002) and the X-ray (Montmerle et al. 1983; Casanova et al. 1995; Grosso et al. 2000; Imanishi et al. 2001).

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** Table 2 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/426/171>

From the perspective of our study of molecular outflows, the protostellar stages of star formation are critical. From the near-infrared spectra, Luhman & Rieke (1999) conclude that roughly 17% of the YSOs are Class I sources, which implies a lifetime of about 0.1 Myr for this stage and the availability of over 20 potential driving sources for powerful molecular outflows. In order to detect the outflows in ρ Oph, a range of surveys at millimetre, infrared and optical wavelengths have been undertaken. Some 15 CO outflows have so far been recorded, where the most prominent examples arise from IRS 44 (Terebey et al. 1989), VLA 1623 (Andre et al. 1990; Dent et al. 1995) and GSS 30 (Tamura et al. 1990). The earlier studies have recently been complemented by the more systematic search from Bontemps et al. (1996), who detected a total of 11 CO outflows in the region. In addition, Sekimoto et al. (1997) found four CO outflows which arise from X-ray emitting protostars and Kamazaki et al. (2003) have added a further three CO outflows.

Atomic jets and Herbig-Haro (HH) objects have been discovered through optical searches at the perimeter of the cloud (Wilking et al. 1997; Gómez et al. 1998; Phelps & Barsony 2004) and at large distances from the cloud core (Wu et al. 2002). The optical studies suggest that the outflows extend over scales up to one degree. Wu et al. (2002) discovered seven groups of HH objects 2–3 pc away from the ρ Oph dark cloud core. Among these, the three brightest objects, HH 549, HH 550, and HH 551, display characteristic HH morphologies of a bow shock or knot with wings or a tail. HH 550 and HH 551 are located more than 1 pc away from the cloud and possibly form a parsec-scale HH flow in Ophiuchus. It is plausible that optical emission lines from embedded flows in the denser clumps are not observed because of the large extinction of $A_V = 50$ –100 mag in the clumps (Wilking & Lada 1983).

In contrast, near-infrared (H_2 2.12 μ m) imaging observations have detected and explored shock-excited knots and jets located in highly obscured areas (Davis & Eisloffel 1995; Dent et al. 1995; Davis et al. 1999; Grosso et al. 2001). These searches have been confined to small regions, typically $5' \times 5'$. However, Gómez et al. (2003) presented the results from near-infrared and optical surveys covering a large portion of the ρ Oph cloud. They chose three partly adjoining regions with a combined area of 480 square arcminutes to survey in the near infrared with the New Technology Telescope (NTT). With an integration time of 480 s, many new H_2 emission knots which could constitute 13 distinct H_2 outflows were detected.

However, the close distance to the ρ Oph molecular cloud, in addition to the optical work of Wu et al. (2002), suggests that typical flow extensions in ρ Oph are of the order of one degree (i.e. a linear flow extent of 2 pc at a distance of 130 pc). Therefore, we need an unbiased search over a field of 1 square degree in order to carry out a complete census of the molecular outflows in the ρ Oph cloud and to determine their connection to the driving sources. Our initial intention was indeed to survey a field this size in both the near-infrared and millimetre wavelength regions. This goal was achieved in our millimetre survey, which is described in Stanke et al. (2004, Paper II). Unfortunately, weather losses and an insufficient allocation of

Fig. 1. The scheme of the survey carried out in the H_2 filter overlaid on the DSS 1×1 degree image. Fields 01 to 10 are labelled here to show the central positions (see Table 1). Solid line boxes indicate the part of the region surveyed with the NTT and dotted line boxes show the supplementary survey using the CAHA 3.5 m.

time resulted in a significantly smaller area being surveyed in the near-infrared. The near-infrared survey was conducted in August 2001 using SOFI at the NTT on La Silla. Additional data were secured at high airmass using the OmegaPrime camera at the Calar Alto 3.5 m telescope. The result is an unbiased 600 s H_2 survey of an area of 1320 square arcmin. The direct purposes of the survey are to determine the sizes and the number of the outflows, and to trace them back to millimetre sources.

2. Observations and data analysis

2.1. Observing strategy

The area covered by our near-infrared observations is shown superimposed on a DSS¹ image in Fig. 1. The seven boxes labelled 01, 02, 03, 04, 05, 08, and 09 outline individual fields of $12'6 \times 12'6$ size which were observed with the near-infrared camera SOFI at the NTT, on La Silla. Data were accumulated during seven first half nights in the period August 2–8, 2001. SOFI is equipped with a HgCdTe 1024×1024 HAWAII detector. We have used a pixel scale of 0.276 arcsec/pixel, which results in an area of $4'7 \times 4'7$ covered in one integration. Images were obtained in the H_2 1–0 S(1) narrow band filter, with pass-band centre at $\lambda = 2.124 \mu$ m and width of 0.028μ m, and in

¹ DSS images were produced at the STSI under US Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

Table 1. List of observed positions shown in Fig. 1 and observing conditions.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Observed position	RA (2000.0)	Dec (2000.0)	Telescopes [†] used	Integration (s)	Seeing (in ")	Noise [*]
Field01	16 ^h 28 ^m 44 ^s .3	−24°53′42″	1	600	0.8	0.76
Field02	16 ^h 27 ^m 56 ^s .1	−24°53′42″	1	600	0.7	0.55
Field03	16 ^h 27 ^m 07 ^s .9	−24°53′42″	1	600	1.2	0.74
Field04	16 ^h 27 ^m 07 ^s .9	−24°42′45″	1	600	0.7	0.85
Field05	16 ^h 27 ^m 56 ^s .1	−24°42′45″	1	600	0.6	0.94
Field06	16 ^h 28 ^m 44 ^s .3	−24°42′45″	2	540	0.9	3.79
Field07	16 ^h 28 ^m 44 ^s .3	−24°31′48″	2	540	1.6	3.36
Field08	16 ^h 27 ^m 56 ^s .1	−24°31′48″	1; 2	450; 270	0.7; 0.7	1.55; 3.33
Field09	16 ^h 27 ^m 07 ^s .9	−24°31′48″	1	600	0.9	0.93
Field10	16 ^h 26 ^m 19 ^s .7	−24°31′48″	2	540	1.2	3.45

† – Used telescopes: 1 ESO/NTT; 2 CAHA 3.5 m.

★ – noise in units of $10^{-18} \text{ W m}^{-2} \text{ arcsec}^{-2}$, see Sect 2.1 for explanation.

the K_s broadband filter, with passband center at $2.162 \mu\text{m}$ and width of $0.275 \mu\text{m}$.

Additional data were obtained at the Calar Alto Observatory using the OmegaPrime camera at the 3.5 m telescope. Note that from Calar Alto, ρ Oph is observable only at airmass greater than 2 at any given time. The resulting noise in the Calar Alto frames is significantly higher than the noise in the SOFI frames (cf. Table 1). The fields covered with OmegaPrime are labelled 06, 07, 08 and 10 and are indicated in Fig. 1 using dotted lines. Field 08 was observed with both SOFI and OmegaPrime. The adopted observing strategy with OmegaPrime was the same as employed with SOFI. The Calar Alto observations were carried out during three first half nights of August 10–13, 2003. Omega Prime (Bizenberger et al. 1998) is equipped with a Rockwell 1024×1024 pixel HAWAII array detector and provides a fixed pixel scale of 0.4 arcsec/pixel . The total field of view covered in one integration is $6'.8 \times 6'.8$. Images were obtained in the narrow band H_2 1–0 S(1) filter centered at $\lambda = 2.125 \mu\text{m}$ and a width of $0.0206 \mu\text{m}$, as well as in the K_s broadband filter, with passband centered at $\lambda = 2.196 \mu\text{m}$ and width of $0.388 \mu\text{m}$.

Our observing strategy was to reach a homogeneous integration time over the entire surveyed region. Therefore, the following observing pattern was adopted. For each of our Fields 01–10, an exposure was obtained at the centre of the field, then the subsequent eight exposures were taken with the telescope offset by steps of $229''$ in $-\text{RA}$, $+\text{Dec}$, $+\text{RA}$, $+\text{RA}$, $-\text{Dec}$, $-\text{Dec}$, $-\text{RA}$, $-\text{RA}$, where RA and Dec are right ascension and declination, respectively (see Khanzadyan 2003, for more details). The resulting overlap of $70''$ is sufficient for accurate mosaicking. Furthermore, at each position, integrations were accumulated adopting a jitter box of 20 arcsec . In this way, a total area of $12'.6 \times 12'.6$ has been covered per field, and a total connected area of some $34'.5 \times 34'.5$ has been covered. In general, total integration times per observed position are 600 s

for the H_2 filter and 120 s for the K_s filter. Table 1 lists the right ascension and declination of the fields, the telescope utilised, the total integration time per field, the average seeing as measured on the images, and the noise in the frames, respectively. The noise in the sky-subtracted images was obtained by averaging the mean deviation of the sky in 10 different object-free areas using $10''$ apertures.

2.2. Data reduction

The data reduction utilised the KAPPA and CCDPACK software developed under STARLINK. Sky frames were constructed from typically 20 object frames and flat fielding was achieved with integrations on a flat field screen, with difference images (lamp on) – (lamp off) used as flats. In the next stage, due to the large amount of data, an automatic registering and mosaicking technique has been employed, using the CCDPACK routines FINDOBJ, FINDOFF, REGISTER, TRANNDF and MAKEMOS. In this manner, the mosaics in all observed Fields have been constructed. Finally the complete observed region mosaics have been constructed in each observed filter by interactive methods provided by the CCDPACK software (PAIRNDF, REGISTER, TRANNDF and MAKEMOSAIC).

2.3. Astrometric calibration

The astrometric calibration was performed in several stages. Firstly we calibrated the entire field presented in Fig. 2, where we achieved about 1.5 arcsec accuracy by using DSS and 2MASS² images to identify the stars, HST guide

² 2MASS two micron all sky survey project is collaboration between The University of Massachusetts and the Infrared Processing and Analysis Center (JPL/Caltech).

Fig. 2. The portion of the ρ Ophiuchi cloud covered by our survey in H_2 1–0 S(1) line + Continuum. New and previously known H_2 1–0 S(1) line objects are marked with squares. Optical Herbig-Haro objects are labelled with triangles. The regions demarcated by large boxes are labelled according to the knot definitions explained in the text and are presented further in Figs. 3 to 14.

star catalogue (GSC³) and SIMBAD⁴ data base to determine the coordinate solution. The resulted astrometry is of course affected by field distortions over the SOFI or OmegaPrime fields, but it gave us a basis for further improvements.

In the second stage, parts with already detected H_2 emission were separated and astrometrically calibrated again using the same data bases as during the first stage. This time we achieved an accuracy of under 0.5 arcsec mainly due to using small individual fields of 2–3 arcmin, which ensures that any field distortion is small. In this way, the coordinates given in Table 2 (only available in electronic form at the CDS) were obtained.

³ **GSC** was produced at the STSI under US Government grant. These data are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope.

⁴ **SIMBAD** is online database, operated at CDS, Strasbourg, France.

2.4. Continuum subtraction

The following systematic approach was employed to reliably extract the “pure” H_2 1–0 S(1) line emission objects.

- Firstly, the H_2 line and K_s images of individual fields were aligned and then blinked with each other ensuring that the stars on both of them have the same brightness on the image display. Objects present on the H_2 line image and absent or faint on the K_s band image were counted as a detection. In this manner, most of the objects in our survey were detected. Hereafter, we will refer to this stage as an “eye” detection.
- Secondly, we separated the fields with already detected objects and performed higher accuracy alignment to ensure that the field distortion effect is small or recognizable. Then PSFs (Point Spread Functions) for stars on both images were constructed and compared with each other to determine the scaling factor which was used to

Fig. 3. Knots f03-01 and f03-02. The main gray-scale image is H₂ 1-0 S(1) line + Continuum and the inverted-gray-scale inserts are smoothed pure H₂ 1-0 S(1) line images, where H₂ line emission features are marked with dashed circles and ellipses. The dashed line on the main picture shows the HH 224 flow direction suggested by Phelps & Barsony (2004) and the solid line shows our suggested flow direction from EM*SR24.

multiply the H₂ 1-0 S(1) line image. This was followed by the actual subtraction of the K_s band image from the already scaled H₂ line image, which enabled us to identify pure H₂ 1-0 S(1) shocked material, but excluded some of the weak “eye” detection.

- Thirdly, before subtracting the K_s band image from the already scaled H₂ line image, both images were processed with an IDL based routine LEEFILT originally implemented by Lee (1986), which is an enhancement process based on unsharp masking. Then, after the subtraction, the resulting image was smoothed with a 3-pixel box. In this way, we confirm all “eye” detections and add new ones. Additionally, images in the inserts of Figs. 3–14 are obtained via this method.

This approach gives satisfactory results when identifying pure H₂ 1-0 S(1) shocked material but, due to the redder central wavelength of the K_s filter in respect to the H₂ line one (see Sect. 2.1), this can cause over-subtraction of the red stars and under-subtraction of the blue stars. Also, due to the fact that the K_s and H₂ images are taken in slightly different weather conditions, after subtraction residuals around the stars might still remain.

2.5. Flux calibration

The flux calibration of the newly discovered H₂ emission objects was obtained via observations of the infrared standard stars Nos. 9155, 9157, 9172, 9175, and 9181 from Persson et al. (1998). After identical data reduction of the science and associated standard frames for each observed field, a specific standard star has been used, which was observed under similar weather

conditions. Then using GAIA⁵ we measure integrated counts from the standard in a fixed aperture (usually 2'' is sufficient in our case), then calculate the flux density expected from the standard at 2.12 μ m and converted it to a flux by multiplying by the filter bandwidth. Finally we calibrate the counts per pixel in each H₂ 1-0 S(1) line image via a comparison of the counts per second from the standard star with the stellar flux (Khanzadyan 2003).

3. Results

3.1. Covered area

The locations of the H₂ emission line features are represented by square symbols in Fig. 2. The final H₂ image has been constructed from the 10 overlapping survey fields Field01–Field10 using more than 3000 individual frames. In the subsequent sections, we employ the following nomenclature in order to identify objects. We prefix all knots according to their placement in the corresponding survey field. In each field, objects are identified according to increasing right ascension. For example, object f10-01 is situated in Field10 and located to the West of object f10-02. In cases where individual objects split up into a number of associated emission knots, we use labels a,b,c, etc.

The areas with detected sources are shown in Figs. 3–14. The larger scale images show the narrowband emission without continuum subtraction. For clarity, we use enlarged inserts in each figure which are continuum subtracted images, displaying the pure molecular hydrogen emission in the 1-0 S(1) line

⁵ **GAIA** is a derivative of the Skycat catalogue and image display tool, developed as part of the VLT project at ESO. Skycat is free software under the terms of the GNU copyright.

Fig. 4. Flow f04-01. The main gray-scale image is H₂ 1-0S(1) line + Continuum and the inverted-gray-scale inserts are smoothed pure H₂ 1-0S(1) line images, where H₂ line emission features are marked with solid lines in order to emphasize the bow shapes. The solid line on the main image shows the suggested direction of the flow and the dash-dotted line indicates the HH 673 flow direction as was suggested by Phelps & Barsony (2004). The position of the HH 673b knot is outside of our image along the dash-dotted line.

(see Sect. 2.4). Each figure contains at least one known source which is labelled according to the following nomenclature:

- BKL: sources from Barsony et al. (1997);
- WL: sources from Wilking & Lada (1983)
- YLW: sources from Young et al. (1986)
- WLY: sources from Wilking et al. (1989);
- BBRCG: sources from Barsony et al. (1989).

Table 2 (only available in electronic form at the CDS) summarises the details of the H₂ objects found in our survey. The second and third columns list the coordinates of each knot, the fourth and fifth column list the fluxes in units of $10^{-18} \text{ W m}^{-2}$ and the corresponding aperture. In several cases, elliptical apertures have been used to derive fluxes. Column 6 cross-identifies our objects with previous detections (Dent et al. 1995; Gómez et al. 2003; Khanzadyan 2003).

3.2. Field01 and Field02

We were unable to identify H₂ emission knots in Field01 and Field02 down to surface brightnesses of $\sim(0.55-0.76) \times 10^{-18} \text{ W m}^{-2} \text{ arcsec}^{-2}$ in 10 arcsec circular aperture (see Table 1). This is despite the fact that the recent optical surveys (cf. Phelps & Barsony 2004) report the presence of a number of HH objects, including HH 416, HH 552, HH 708, and HH 709. The DSS image (see Fig. 1) suggests that the extinction of the cloud in this region is low compared to say Field05 or Field09. The environment may be similar to that of HH 34, where the optical emission also lacks a pronounced

near-infrared counterpart (Reipurth et al. 1986). Thus, the optically detected HH objects in Field01 and Field02 may trace emission which arises in predominantly atomic gas of quite low density.

3.3. Field03

Figure 3 shows a section of Field03 where new H₂ emission knots have been detected. The two continuum subtracted inserts for f03-01a,b,c and f03-02a,b display the morphology of the H₂ emission. The group f03-02 corresponds to the optically detected Herbig-Haro object HH 224S (Phelps & Barsony 2004). However, we do not detect H₂ emission from HH 224 and HH 224N which are indicated in Fig. 3 with triangles. Phelps & Barsony (2004) stipulate that HH 224S is part of a flow which is shown by a dashed line in Fig. 3. We note, however, that HH 709, HH 224, f03-01a,b,c, f03-02a,b, and HH 418⁶ are aligned along a NW-SE direction (indicated by a solid line) which passes through EM*SR 24 (Struve & Rudkjøbing 1949; Wilking et al. 1989). The star EM*SR 24 (WLY 1-3) coincides with our millimetre source MMS1 of Stanke et al. (2004, Paper II). Alternatively, we note that objects f03-01a,c, f05-01 and f05-03⁷ are aligned in the NE-SW direction. Our millimetre survey does not, however, identify a dense dust core along the latter flow

⁶ HH 709 and HH 418 are outside the bounds of Fig. 3. See Fig. 2 for a broader view.

⁷ f05-01 and f05-03 are outside of the region displayed in Fig. 3. See Figs. 2 and 6 for broader views.

Fig. 5. The region overlapping Field04 and Field05 with knots f04-02 to f04-06. Arrows directed from YLW 15 and YLW 16 indicate the proposed flows. Main gray-scale image is H₂ 1-0 S(1) line + Continuum and the inverted-gray-scale inserts are smoothed pure H₂ 1-0 S(1) line images, where H₂ line emission features are marked with dashed circles and ellipses.

direction. (As noted earlier, the appearance of stars in the H₂ inserts for f03-02 is due to the variable seeing in the H₂ and K_s filters.)

3.4. Field04

3.4.1. f04-01

Figure 4 shows objects f04-01a and b of Field04. Both features possess a pronounced bow shock shape with a flow direction pointing towards the south-west. The f04-01a structure coincides with the position of HH 673 (Phelps & Barsony 2004). A suggestion here is that HH 673 is linked with HH 673b, (not detected in H₂ line and situated outside of our image) forming a flow in the NW-SE direction. That flow direction is indicated by the dash-dotted line in Fig. 4. However, because of the pronounced bow shapes of both f04-02a and f04-01b, we infer that they arise from a

flow connecting both knots with a flow direction represented by the solid line. Both knots appear in the prolongation of the f08-01 flow which is located to the NE (cf. Sect. 3.7 and Fig. 8). Two Herbig-Haro objects, HH 417 in the NE and HH 418 in the south-west, appear along the projection of our suggested flow direction as evident in Fig. 2. They were not detected in the H₂ line. The flow, if confirmed, would stretch half a degree.

3.4.2. f04-02 to and f04-06

Figure 5 shows a region which overlaps with Field04 and Field05. It contains a total of 17 new H₂ emission line objects. Part of this region has already been observed by Gómez et al. (1998), who detected the Herbig-Haro object (GW98) A2 (later renamed as HH 674 by Phelps & Barsony 2004). Our observations yield two major flows from YLW 16

Fig. 6. Part of Field05 where knots f05-01, f05-02 and f05-03 are situated. Main gray-scale image is H_2 1-0 S(1) line + Continuum and the inverted-gray-scale inserts are smoothed pure H_2 1-0 S(1) line images.

and from YLW 15. The two proposed flows seem to be parallel on the sky. f04-02, f04-05a, b, f04-05d, and f04-05e, f, h lie along one axis that runs through YLW16, while f04-03a, f04-03b, f04-03c, d, and f04-03e, f lie along a second flow axis centred on YLW15. These two flow axes are marked with solid line arrows in Fig. 5.

To the south-west of the YLW 15, the point-like object f04-02 is detected at 2σ above the noise in the sky subtracted image of Fig. 5. Following the stipulated flow direction from YLW 15, we see the point-like objects f04-03a to the SW of YLW 15, and f04-03b, f04-03c and d, f04-03e and f towards the NE. Towards the immediate SW of YLW 16, we identify objects f04-05a, b, c and towards the NE, objects f04-05d and f04-05e-h. The position of object f04-05d agrees with HH 674.

Located somewhat off the NE-SW flow direction from YLW 15 is f04-04, and north of YLW 16 f04-06 appears. The feature f04-04 is located some 40 arcsec to the SE of WLY 2-32b and the possibility exists that the two are related. Alternatively, we note that f04-04 and f04-06 are roughly diametrically opposed to WLY 2-42.

The continuum subtracted images show remnant emission around the young stellar object YLW 16 which arises from a reflection nebulae. Imaging polarimetry measurements of the YSO obtained by Lucas & Roche (1998) (their Fig. 5) reveals the dust distribution in the bipolar cavity of the YLW 16 core region. Our millimetre survey (cf. Paper II: Stanke et al. 2004) results in the detection of several millimetre sources along the NE-SW flows from YLW 15 and YLW 16.

Fig. 7. The f05-04 flow. Main gray-scale image is H_2 1-0 S(1) line + Continuum and the inverted-gray-scale inserts are smoothed pure H_2 1-0 S(1) line images. The position of the MMS126 source from our Stanke et al. (Paper II: 2004) is marked with an asterisk.

3.5. Field05

3.5.1. f05-01 to f05-03

Figure 6 shows the newly discovered H_2 emission objects f05-01, f05-02, and f05-03, located in Field05. Object f05-01 has a morphology which is reminiscent of a bow shock pointing towards the SE or SW. Because of its proximity to YLW 15 and YLW 16 (about 3' to the NW), it may very well arise from a NW-SE flow from this region, and possibly be connected to f09-01 (see Fig. 2). Object f05-03 has an elongated shape with the large semi-major axis pointing towards YLW 16. However, it is intriguing to speculate that f05-01, f05-03, and f03-01a, c form part of a gigantic flow which extends from the NE to SW (cf. Fig. 2 and Sect. 3.3). This possibility will be further discussed by Smith et al. (2004, Paper III).

Knots f05-02a and b, shown in the second insert of Fig. 6, are diametrically opposed to BKL J162745-244454 and located in the immediate vicinity of this object. We purport they arise from an edge-on disk system with a bipolar outflow. The authenticity of the knots was proved by blinking the continuum image with the line image as it is explained in Sect. 2.4. The residuals around the star BKL J162745-244454 are present simply due to the fact that the shape of the PSF changes due to field rotation, e.g., diffraction patterns from the secondary support rotate when observing with an alt-azimuth telescope.

3.5.2. f05-04

Figure 7 shows the three extended H_2 emission knots f05-04a-c which is one of the most intriguing flows discovered in our survey. It consists of several extended emission

Fig. 8. Flow **f08-01**. The solid line indicates the suggested S-shaped outflow. Main gray-scale image is H_2 1–0 S(1) line + Continuum and the inverted-gray-scale inserts are smoothed pure H_2 1–0 S(1) line images.

features which are aligned in the NE to SW direction. Most interestingly, our millimetre survey (Paper II: Stanke et al. 2004) has resulted in the discovery of a Class 0 source, MMS126, located right between knots **b** and **c**. The position of MMS126 is marked by the asterisk in Fig. 7. We do not find additional emission objects in the north-eastern or south-western prolongation of the flow, which suggests that either the flow is very young indeed or that the environment is diffuse.

3.6. Field06 and Field07

We do not detect H_2 emission objects in Field06 and Field07 down to the sensitivity limits of $3.3\text{--}3.8 \times 10^{-18} \text{ W m}^{-2} \text{ arcsec}^{-2}$ in a 10 arcsec circular aperture (see Table 1). Both fields contain a number of optical HH objects including HH 420, HH 420b, and HH 417. Because observations of Field06 and Field07 were carried out from Calar Alto at very high airmass, the noise is significantly higher than in the other fields (cf. Table 1). In addition, the extinction particularly in Field06 could be rather high, as judged from e.g. Fig. 1. The non-detection of near-infrared emission may then result from the excessive noise. Alternatively, the optical HH objects arise at the near-side of the cloud and trace emission which arises in less dense material, in a medium which may not be dense enough to shock-excite H_2 emission.

3.7. Field08

We discover 7 H_2 1–0 S(1) line excited knots in Field08, as shown in Fig. 8. Knots **f08-01a** and **b** are situated west from

the source YLW 52 and knots **f08-01d** to **h** are in the east. YLW 52 is a Class I protostar and exhibits a featureless *K*-band spectrum (Greene & Lada 2000). Features **f08-01e**, **f** and **g**, **h** appear to arise from the walls of a cavity, possibly excited by oblique shocks in an S-shaped flow elongated almost E–W. The stipulated flow direction is represented by the solid line in Fig. 8. We note that the objects **f09-01** are located at the south-western prolongation of the flow direction (see Sect. 3.8.1).

Object **f08-01a** has been studied by Grosso et al. (2001), who discussed the possibility that **f08-01a** arises from two interacting flows which originate from YLW 52 and from YLW 15, (situated outside the bounds of Fig. 8, roughly south-west from **f08-01a** and is separated by about 8 arcmin).

3.8. Field09

3.8.1. f09-01

Figure 9 shows knots **f09-01a–g** of Field09. The knots **f09-01a–f** were discovered by Gómez et al. (2003), displayed in their field (GSWC2003)3. BBRCG 27 (WL 10) is a Class II source from which a CO outflow emerges (Sekimoto et al. 1997). Gómez et al. (2003) suggested that the emission arises from multiple flows which overlap. Their conclusion is based on the fact that the region contains a Class I (WL15) and several Class II sources (WL11, WL14, WL21).

Our study results in the detection of an additional knot **f09-01g**, which coincides with the red lobe of the ^{12}CO outflow detected by Sekimoto et al. (1997). We note that knots **f09-01b** and **d** are on the same axis as the flow arising

Fig. 9. Flow f09-01 in H₂ 1-0 S(1) line + Continuum.

from WL 6. This flow forms f09-02 (cf. Sect. 3.8.2), which is located SW of the f09-01 knots. We also note that the bow-shape morphology of f09-01a and the location of knots f09-01a, c, and e suggest a NW-SE separate and unrelated flow direction which, if followed towards the SE, may very well generate the bow of f05-01. In this respect, the suggestion of Gómez et al. (2003) that the emission knots in (GSWC2003)3 or f09-01 arise from physically distinct flows is supported.

Alternatively, it is worth mentioning that the f09-01 knots might well originate from one flow if we consider a fast precession jet mechanism as discussed by Rosen & Smith (2004), where some simulations of the H₂ 1-0 S(1) line emission show a great similarity to the picture we have here.

3.8.2. f09-02 and f09-03

Figure 10 shows part of Field09 where knots f09-02 and f09-03 are located. Both knots were discovered by Gómez et al. (2003). The two inserts in Fig. 10 show nicely the bow like morphologies of both knots. Object f09-02 has a bow-like structure which suggests a flow direction to the NE. Its morphology strongly suggests that it originates from a flow from WL 6 (Wilking & Lada 1983). The stipulated flow direction is represented by straight lines and arrows in Fig. 10. This conclusion is in agreement with Gómez et al. (2003). On the other hand, the pronounced bow-shock morphology of f09-03 suggests a flow direction towards the NW and that WLY 2-48 is the driving source. The separation of 3' corresponds to an extent of 0.11 pc at an adopted distance of 130 pc. All this suggests that f09-02 and f09-03 are independent flows.

Fig. 10. Region with knots f09-02 and f09-03. Solid lines indicate the proposed source and knot connections. Main gray-scale image is H₂ 1-0 S(1) line + Continuum and the inverted-gray-scale inserts are smoothed pure H₂ 1-0 S(1) line images.

3.9. Field10

3.9.1. f10-01

Figure 11 shows the chain of nine H₂ emission line knots f10-01a-g which extends in the NE-SW direction from YLW 31. The stipulated flow direction is given by a straight line in Fig. 11. The flow extends over a distance of 7.7 arcmin or 0.3 pc. We propose YLW 31 as the driving source because of the accurate alignment of the individual knots with respect to this Class II source (Bontemps et al. 2001).

3.9.2. f10-02

Figure 12 shows the isolated object f10-02 whose bow-type morphology suggests a flow direction towards the NE. The flow direction is indicated in the insert of Fig. 12. The emission pattern suggests that knot a is a part of a fading wing of the bow and knot b arises from the apex of the bow. The purported flow direction towards the NE is supported by the location of HH 419 (outside of the picture) some 3 arcmin towards the eastern prolongation (see Fig. 2).

3.9.3. f10-03

Figure 13 shows a group of knots situated in the upper outskirts of Field10 which we name f10-03 (see Fig. 2). The shape of the bow-like feature, clearly seen on the insert frame as knot b, suggests that the flow originates from a general northern direction. A NE-SW direction is suggested by the location of HH 79 and HH 711 about 9 and 14 arcmin respectively towards the north-east as can be seen in Fig. 2.

Fig. 11. Flow f10-01. Solid line shows the extent of the proposed flow. Main gray-scale image is H_2 1-0 S(1) line + Continuum and the inverted-gray-scale inserts are smoothed pure H_2 1-0 S(1) line images.

Fig. 12. The bow structure of f10-02. Main gray-scale image is H_2 1-0 S(1) line + Continuum and the inverted-gray-scale insert is smoothed pure H_2 1-0 S(1) line image.

Fig. 13. The f10-03 group of knots. Main gray-scale image is H_2 1-0 S(1) line + Continuum and the inverted-gray-scale insert is smoothed pure H_2 1-0 S(1) line image.

3.9.4. f10-04

Figure 14 shows a group of knots located in the south-eastern vicinity of VLA 1623. We assign names f10-04a-m to the individual emission knots. The H_2 and CO emission of this region has been studied in detail by Dent et al. (1995), whose knots H1, H2, and H3 correspond to f10-04h, f10-04g,

and f10-04d, e, respectively. Deeper observations by Gómez et al. (2003) resulted in the discovery of additional emission which corresponds to our knots f10-04c, f, i, j, l. The molecular hydrogen is spatially correlated with the blueshifted CO emission (Andre et al. 1990; Dent et al. 1995) and the solid line drawn in Fig. 14 corresponds to the flow direction. Our observations has uncovered further knots f10-04a,b along the

Fig. 14. Flow f10-04. The solid curved line shows the extent of the suggested flow. Main gray-scale image is H₂ 1-0 S(1) line + Continuum and the inverted-gray-scale insert is smoothed pure H₂ 1-0 S(1) line image, where H₂ line emission features are marked with dashed circles and ellipses.

north-west prolongation of the flow and features at some 1.5σ above the background noise in the south-east prolongation, labelled with question marks in Fig. 14. Knots f10-04i-m have been identified by Gómez et al. (2003) but were thought to arise from the separate flow (GSWC2003) 21. Our data suggest that all of the knots f10-04a-m arise from the VLA 1623 outflow. We note that our fluxes are about a factor of 2 lower than the fluxes of Dent et al. (1995) for knots f10-04h, f10-04g, and f10-04d, e. We suspect inaccurate flux determination from our observations as the observations were obtained at an airmass of 2.2. However, shock waves propagating in jets are predicted to rapidly decay in strength (Smith et al. 1997). Given the small size of the knots and the duration of over nine years between observations, flux variations should be expected. A proper motion of 2 arcsec would ensue given bow shock speeds of 130 km s^{-1} in the plane of the sky. Therefore, monitoring of these features would be illuminating for jet models.

4. Summary

We have searched a wide area of the main star-forming cloud in ρ Ophiuchus for emission from vibrationally-excited molecular hydrogen. The emission we detect originates from shock waves since (a) there are no nearby sources of ultraviolet radiation and (b) the emission originates in discrete knots and wings rather than the illuminated rims of dense clumps or pillars. A quantitative analysis, in combination with a detailed comparison to our millimetre survey, will be undertaken in Smith et al. (2004, Paper III, in preparation). Here, we have investigated

the links between emission knots and chains of knots in order to constrain the location of driving sources.

The number of distinct protostellar outflows can be estimated from Fig. 2. We find that 10 outflows are sufficient to account for all the H₂ emission. Even so, there are alignments which could reduce the number. In fact, if the average size of a protostellar outflow were 0.6 pc, (e.g., Stanke 2003), then it would extend 15 arcmin. In other words, the driving protostar may be located far from the molecular hydrogen features. On the other hand, quite compact H₂ outflows are also identified (e.g. f05-4).

The overall distribution of H₂ objects follows the network of cloud filaments. This suggests that the outflow components only become detectable when they encounter dense cloud material rather than dragging out and shocking molecular material. Hence, H₂ is not a good tracer of outflows that extend beyond the bounds of molecular clouds.

The minimum jet power required to drive the H₂ shocks can be estimated here. The integrated 1-0 S(1) H₂ fluxes for the flows f05-4, f08-01 and f10-04 are 3.4 , 12.9 and $29.5 \times 10^{-17} \text{ W m}^{-2}$. These convert to the very small line luminosities of 1.8 , 6.8 and $15.6 \times 10^{-5} L_{\odot}$, respectively, for the distance of 130 pc. The total H₂ luminosity from the radiating shocked layers is 10–20 times these values (Smith 1995). However, dense hydrodynamic jets are found to be extremely inefficient at thermalising the available power. Hydrodynamic simulations of diverse evolving outflows yield a ratio of jet to 1-0 S(1) luminosity of 300–3000 (Rosen & Smith 2004). The larger values correspond to highly collimated ballistic flows in which the jet and leading bow shock both move at high speed. The lower

values correspond to precessing flows. On the other hand, we suspect that a magnetic field cushions the shock, channelling considerably more energy into infrared line emission while, contrarily, the dust extinction tends to screen it out. The result, found to be consistent with the data for protostellar outflows in general (Froebrich et al. 2003), is that jet powers are probably 1000 times the observed 1–0 S(1) luminosity. We thus conclude that driving jet powers are in the range 0.02–0.2 $L_{\odot}$.

The majority of outflows are directed into the NE–SW quadrants, transverse to the degree-scale filamentary cloud structure. This could be an intrinsic property or could indicate that extinction limits our ability to detect the outflows. In this context, Kamazaki et al. (2003) found three CO outflows in ρ Oph A all aligned into the NW–SE quadrants with the blue-shifted material directed towards the south-east. Only one of these three CO outflows is evident in our H₂ survey. Hence, although the number of H₂ outflows is roughly consistent with both the number of Class 0 and Class I protostars and the number of CO outflows in the same area (Bontemps et al. 1996), a deeper examination is absolutely necessary (Paper III: Smith et al. 2004, in preparation).

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