

Proper motions of embedded protostellar jets in Serpens[★]

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ABSTRACT

Context. To investigate the dynamical properties of protostellar jets.

Aims. Determine the proper motion of protostellar jets around Class 0 and Class I sources in an active star forming region in Serpens. **Methods.** Multi-epoch deep images in the 2.122 μm line of shocked molecular hydrogen, $v=1-0\text{ S}(1)$, obtained with the near-infrared instrument NOTCam over a time-scale of 10 years, are used to determine proper motion of knots and jets. K-band spectroscopy of the brighter knots is used to supply radial velocities, estimate extinction, excitation temperature, and H_2 column densities towards these knots.

Results. We measure the proper motion of 31 knots over different time scales (2, 4, 6, and 10 years). The typical tangential velocity is around 50 km/s for the 10 year base-line, but for shorter time-scales a maximum tangential velocity up to 300 km/s is found for a few knots. Based on morphology, velocity information and the locations of known protostars, we argue for the existence of at least three partly overlapping and deeply embedded flows, one Class 0 flow and two Class I flows. The multi-epoch proper motion results indicate time-variable velocities of the knots, for the first time directly measured for a Class 0 jet. We find in general higher velocities for the Class 0 jet than for the two Class I jets. While the bolometric luminosities of the three driving sources are about equal, the derived mass flow rate \dot{M}_{out} is two orders of magnitude higher in the Class 0 flow than in the two Class I flows.

Key words. stars: formation – ISM: jets and outflows – ISM: Herbig-Haro objects – ISM: kinematics and dynamics

1. Introduction

Protostellar jets are spectacular manifestations of the birth of a star. Supersonic and collimated jets drive bipolar outflows of molecular gas, removing angular momentum from – and allowing accretion onto the protostar. The origin of the jets is poorly understood, but a tight relation between the accretion disk and the jet is evident in magneto-hydro-dynamic models. For a recent review on jets and outflows see Frank et al. (2014). The power carried by the jet is expected to be proportional to the accretion luminosity of the central star, suggesting that protostellar jets from the youngest protostars have higher velocities. As shown by Bontemps et al. (1996) the youngest Class 0 sources (ages from a few 10^3 to a few 10^4 yrs) have more energetic CO outflows than the more evolved Class I protostars. Studies of shocked molecular hydrogen in the jets have shown an empirical relation between the H_2 jet luminosity and the bolometric luminosity of the driving source, but found no clear distinc-

tion between Class 0 and Class I sources (Caratti o Garatti et al. 2006).

Plasma is ejected in the form of a jet which interacts with the circumstellar medium via radiative shocks, giving rise to observable emission in various lines over a large spectral range (Reipurth & Bally 2001; Bacciotti et al. 2011). The near-infrared emission from such shocks is mainly in lines of [Fe II] and the ro-vibrational lines of molecular hydrogen. The observed features of the latter are referred to as Molecular Hydrogen emission-line Objects (MHO's). In particular, the $v=1-0\text{ S}(1)\text{ H}_2$ line at 2.122 μm is a good tracer of shock excited emission in low-velocity shocks, and the 2 μm region suffers less from extinction than optical lines and makes it possible to observe the most embedded flows, potentially the very youngest jets.

Protostellar jets are often complex morphological structures, composed of a multitude of knots and features, and the school-book example of a symmetric bi-polar jet is rarely observed. In regions of dense star formation one frequently finds asymmetric flows, jets without counter-jets, variable ejection, colliding knots, precession, or two jets that are interacting. Mapping the kinematics of the individual knots will facilitate identification of whole entities of jets and make it possible to separate individual

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flows in crowded regions. This is required in order to study the kinematic and physical properties of the jets and their driving sources.

Two-epoch proper motions will give the average tangential velocities between the two epochs, while multi-epoch imaging will allow us to investigate how velocities may vary. Recent multi-epoch (> 2 epochs) measurements in the optical as well as the near-IR of nearby jets in Taurus and Chamaeleon have revealed time-variable proper motions and even interaction among knots (Bonito et al. 2008; Caratti o Garatti et al. 2009). In order to determine the velocities of protostellar jets, we need to identify the individual flows and their driving sources. To do this we are in the need of both proper motion and radial velocity information.

In this paper we study the dynamics of the individual knots of embedded protostellar jets in the Serpens NH3 cloud, also referred to as the Serpens/G3-G6 region or Serpens Cluster B (see Eiroa et al. (2008) for a review of the region). These jets were first presented in Djupvik et al. (2006) together with new protostar candidates discovered from a near-IR, mid-IR, submm and radio study of the region. Based on morphology only we tentatively identified the driving sources to be the new Class 0 candidate MMS3 for the North-South oriented jet, and a double Class I for the NE-SW oriented jet. MMS3 was confirmed by Enoch et al. (2009) in their extensive protostar survey (where it is named Ser-emb-1) to be an *early* Class 0 of very low temperature. While being presumably the youngest protostar in Serpens, it has already developed a protostellar disk (Enoch et al. 2011). Studying these jets allows for a comparison between Class 0 and Class I jets in the same region.

Due to the large cloud extinction to this embedded cluster, these jets are not detected in the optical. No extended emission is found in deep $H\alpha$ imaging except for the faint Herbig-Haro object HH 476, discovered in an optical [SII] survey by Ziener & Eislöffel (1999), and some emission around the association of bright T Tauri stars named Serpens/G3-G6 (Cohen & Kuhl 1979).

We obtained deep H_2 line imaging in four epochs over 10 years. The first epoch of data (2003) was already published in Djupvik et al. (2006), and the second epoch (2009) was taken during the Nordic-Baltic Summer School in Turku, Finland.¹ Preliminary results, carried out as a student project during the course showed that proper motions indeed could be measured between 2003 and 2009. The data is re-reduced here, and in addition, we obtained two more epochs (2011 and 2013), as well as K-band spectroscopy of selected knots, all obtained with NOTCam at the Nordic Optical Telescope.

Section 2 describes the target field, observations and data reduction, Sect. 3 presents the proper motion, fluxes, and radial velocity measurements of the knots, as well as the identification of three distinct flows and their velocities, while Sect. 4 describes the derivation of physical parameters for the three flows, and Sect. 5 gives our summary and conclusions.

2. Target field, observations, and data reductions

2.1. Target field

The Spitzer/IRAC image in Fig. 1 showing the $3.6 \mu\text{m}$ (blue), $4.5 \mu\text{m}$ (green) and $8 \mu\text{m}$ (red) bands gives an overview of the

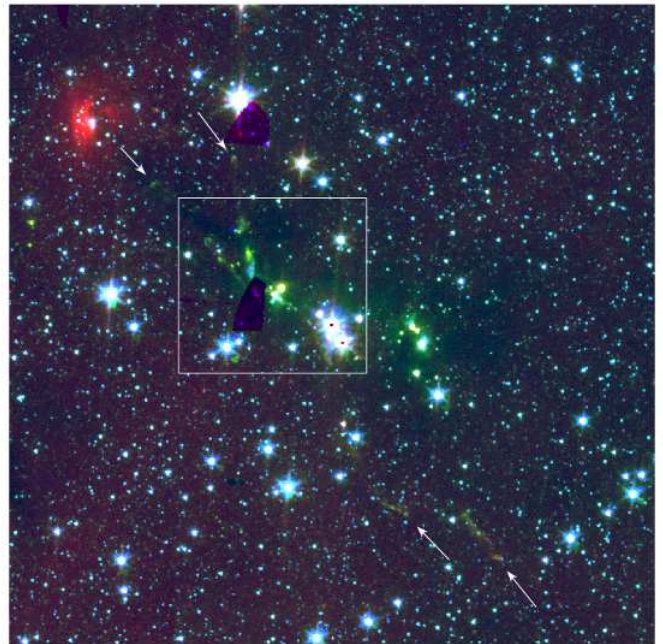


Fig. 1. Overview of the Serpens/G3-G6 region (also called Serpens Cluster B and the Serpens NH3 cloud) as seen by IRAC/Spitzer in $3.6 \mu\text{m}$ (blue), $4.5 \mu\text{m}$ (green), and $8 \mu\text{m}$ (red). North up, East left. Total FOV $\approx 15' \times 15'$. The jets are mainly enhanced in the $4.5 \mu\text{m}$ band. The $\approx 4'$ field monitored with NOTCam for proper motions is marked white and shown in Fig. 2. The white arrows point to two bow-shock shaped features outside our monitored field to the North and North-East and two jet-like features in the South-West region.

Serpens NH3 region, also called Serpens Cluster B. It is centred on a group of four optically visible and very bright T Tauri stars Ser/G3-G6 (Cohen & Kuhl 1979). Two NH3 cores are located to either side, one to the NE and another to the SW, where active star formation takes place and a number of Class 0 and Class I objects are found (Djupvik et al. 2006; Harvey et al. 2006, 2007). The multi-epoch H_2 line imaging with NOTCam was obtained in the region outlined by the white box. The jets stand out in the $4.5 \mu\text{m}$ band emission (green), and apparently they extend beyond the field covered by NOTCam. In Fig. 2 the jets are outlined by the H_2 line emission at $2.122 \mu\text{m}$. With a narrow-band continuum image centred at $2.087 \mu\text{m}$ obtained in 2003 the line emission knots were easily distinguished from the continuum (Djupvik et al. 2006). In the Molecular Hydrogen Emission-Line Objects (MHO) catalogue (Davis et al. 2010) the objects studied in this paper are numbered MHO 2233, MHO 2234, and MHO 2235, their positions being sketched in Fig. 2. Judging from the Spitzer image, it seems that MHO 2233 extends further to the North-East, and possibly MHO 2235 to the South-West. MHO 2234 extends further to the North, and our 2009 observations confirm $2.122 \mu\text{m}$ emission in the northernmost bow-shaped feature seen in the IRAC image in Fig. 1, but we have only one epoch of data for it.

Each of the MHO objects are composed of a number of smaller knots which we identify and name according to the guidelines established in Davis et al. (2010). It is not clear, however, from the 2D morphology which knot belong to which jet and how many jets there are. Based on proper motions and radial

¹ Nordic-Baltic Optical/NIR and Radio Astronomy Summer School: “Star Formation in the Milky Way and Nearby Galaxies”, 8-18 June 2009, Turku, Finland. See URL <http://www.not.iac.es/tuorla2009/local/>

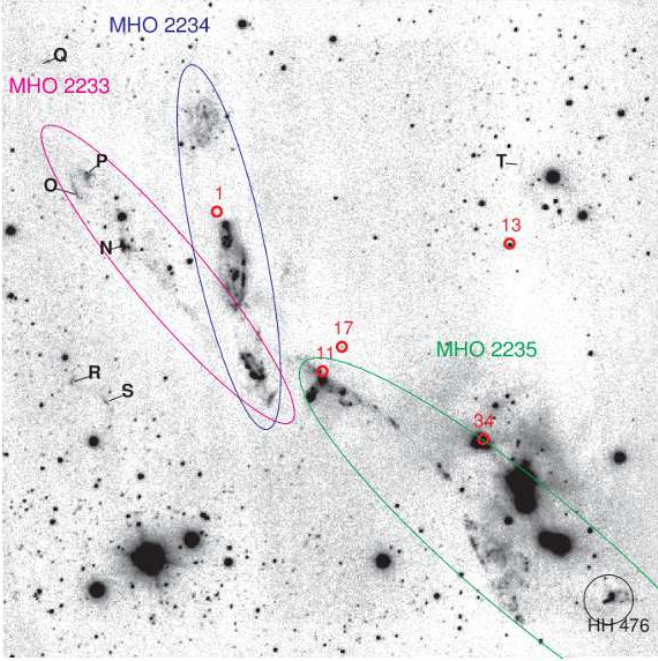


Fig. 2. Deep H_2 + continuum ($2.122 \mu\text{m}$) narrowband NOTCam image of the $\approx 4'$ field observed in this multi-epoch study. North up, East left. Naming of jet structures according to the MHO Catalogue is sketched: MHO 2233 (magenta), MHO 2234 (blue), and MHO 2235 (green). The previously known HH 476 is marked. Red circles show the positions of Class 0 and Class I protostars, the ID number according to designations by Enoch et al. (2009), for instance 1 refers to the Class 0 source Ser-emb-1, which is named is MMS3 in Djupvik et al. (2006). Only a few knots are identified with letters here, and the majority are identified in zoomed-in regions in the following figures.

velocities we show in the following that we find three jets driven by three protostars.

2.2. Imaging

The Nordic Optical Telescope’s near-IR Camera/Spectrograph, NOTCam², was used to obtain deep multi-epoch narrow-band images in the H_2 $v=1-0$ S(1) line at $2.122 \mu\text{m}$ (NOT filter #218) in order to measure proper motions. Four epochs, hereafter referred to as ep1, ep2, ep3, and ep4, are sampled at the years 2003, 2009, 2011, and 2013. The four deep images were obtained with the same instrument, but ep1 was imaged with the NOTCam engineering grade array, while the science array was used for the other three epochs. The wide-field camera of NOTCam has a pixel scale of $0.234''/\text{pix}$ and a $4' \times 4'$ field of view. The deep imaging of the extended emission was mostly performed in beam-switch mode to correctly estimate the sky. In these cases the template NOTCam observing script “notcam.beamswitch” was used to obtain a 9-point grid with small-step dithering both ON target and in the OFF field, going alternately between the ON and OFF regions. The OFF field was chosen either to the East, the West or the North of the central field, the West field being the optimal choice, as it contained no bright disturbing stars whose persistency would affect the background estimate.

² NOTCam is documented in detail on the URL <http://www.not.iac.es/instruments/notcam/>.

Table 1. Observing log for NOTCam imaging used in this paper.

Date	Filters	Epoch	Total exptime (sec)
28 May 2003	218,230	ep1	2000, 2000
29 May 2007	J,H,Ks,218,210	-	450, 450, 450, 900, 900
10 May 2009	218	ep2	540
11 Jun 2009	218	ep2	2100
13 Aug 2011 ¹	218	ep3	2700
25 May 2013	218	ep4	2430

⁽¹⁾ This epoch does not cover the eastern part of the field.

In the North field we found an additional bow-shaped feature emission line object in 2009. In the 2003 epoch no beamswitch was applied, only small-step dithering around the target field. All narrow-band images were obtained with the ramp-sampling readout mode, where the detector is read a number of times during the integration, typically using 60s integrations with 10 equally spaced readouts. A linear regression analysis is performed pixel by pixel through all reads to obtain the final image.

Table 1 lists the various observations and filters used. The filter ID numbers are according to the internal NOT id numbers, where 218 refers to the filter centred on the $v=1-0$ S(1) line at $2.122 \mu\text{m}$, while 210 and 230 refer to narrow-band filters representing the continuum emission at 2.267 and $2.087 \mu\text{m}$, respectively. For all filters differential twilight flats were obtained every night. For flux calibration two standard star fields were observed before and after the target on the photometric night of May 25th 2013, our reference epoch.

The images were reduced using IRAF³ and a set of scripts in an external IRAF package notcam.cl v2.6, made for NOTCam image reductions. All individual raw images were corrected for zero valued bad pixels and hot pixels by interpolation and then divided by the master flats obtained from typically 8 differential twilight flats per filter per night. By using differential flats, the thermal and dark emission is eliminated from the flats. The individual target frames were then sky subtracted using the off fields obtained in beamswitch mode or the dithered target images themselves. After this step all individual images were corrected for the internal camera distortion. For data from 2009 and onwards we use the distortion model for the K_S -band available on the NOTCam calibration web page. For the 2003 data set, a different distortion model was developed based on data from the same night. After distortion correction, all dithered images were registered and combined to form one deep image per epoch.

For flux calibration we used the zeropoint offset between the K_S and the H_2 line filter (#218) found from 8 standard stars in photometric conditions in epoch 4 to be 2.56 ± 0.01 magnitudes, giving a zeropoint for the H_2 line filter of 19.94 mag (for 1 ADU/sec, Vega magnitudes). Assuming the standards have equal flux at 2.12 and 2.14 (K_S) μm , we use the relation for a zeroth magnitude star at $2.121 \mu\text{m}$: $F_\lambda = 4.57 \times 10^{-10} \text{ W m}^{-2} \mu\text{m}^{-1}$ (Tokunaga & Vacca 2005), and the FWHM of the filter ($0.032 \mu\text{m}$), to arrive at a flux conversion of $1.54 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ for 1 ADU/sec. The standard deviation of the background in the 2350s deep image of epoch 4 is $1.5 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$, and the brightest knot, MHO 2235-B, peaks at $1.65 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$.

In addition, we obtained broad-band JHKs images to illustrate the extinction in the region, the filters and exposure times

³ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

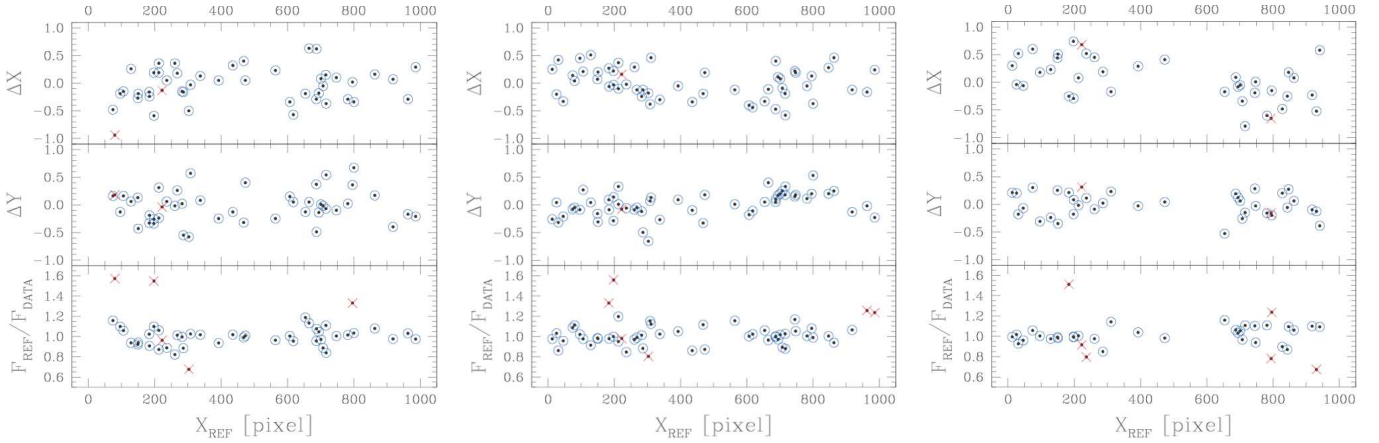


Fig. 3. Relative position accuracy between epochs checked on stars after the final registration (panels ΔX and ΔY) and flux matching accuracy checked after seeing and flux matching (lower panels). The ΔX and ΔY values are the offsets in X and Y (in pixels) between the measured epoch and the reference epoch (i.e. epoch 4). Epoch 1 is shown to the left, epoch 2 in the centre, and epoch 3 to the right, all plotted with respect to reference X-pixel. In the lower panels we show the flux ratio for the same stars. Black dots indicate all stars, red crosses show stars rejected due to large FWHM and/or high flux ratio, and blue circles indicate stars used for the accuracy calculations.

are listed in Table 1. We have also used archive Spitzer data to complement our near-IR imaging with the mid-IR bands of IRAC (Fazio et al. 2004). An RGB colour coded IRAC image using the $3.6 \mu\text{m}$ (blue), the $4.5 \mu\text{m}$ (green) and the $8 \mu\text{m}$ (red) bands is presented in Fig. 1. The jet clearly stands out in green by enhancing the cuts for the emission in the $4.5 \mu\text{m}$ band, a wavelength region with many H_2 lines. Note that central parts of both jets have masked out areas in both the 3.6 and $4.5 \mu\text{m}$ bands. The IRAC imaging was obtained in 2004.

2.3. Spectroscopy

K-band spectroscopy was obtained with NOTCam on October 12th 2011 and March 16th and 17th 2014, in most cases including several knots in the slit for each pointing. The instrument setup was: grism #1, the $128 \mu\text{m}$ slit (a longslit of width $0.6''$ or 2.6 pixels), and the K-band filter #208 used to sort the orders. This covers the range from 1.95 to $2.37 \mu\text{m}$ with a dispersion of $4.1 \text{ \AA}/\text{pix}$, giving a spectral resolution $\lambda/\Delta\lambda$ of about 2100 for the slit used. The slit acquisition was obtained with a previously set rotation angle, calculated from the deep images, and using fiducial stars for alignment. Before acquiring the target on slit, the exact position of the slit was measured. The spectra were obtained by dithering along the slit in an A-B-B-A pattern while auto-guiding the telescope. The integration time was 600s per slit position, reading out the array every 60s while sampling up the ramp. Argon and halogen lamps were obtained while pointing to target in order to minimize effects due to instrument flexure and to improve fringe correction. To correct the spectra for atmospheric features we used either HIP92904 (B2 V), HIP91322 (A2 V), or HIP92386 (A1 V) as telluric standards and observed them right after the targets. Darks were obtained with the same exposure time and readout mode as the target spectra, mainly for constructing a hot pixel mask.

For each night hot pixel masks were constructed from darks taken with the same integration time and readout mode as the target spectra. Zero-pixels and hot pixels were corrected for by interpolation in all images. The individual A-B-B-A spectra were sky-subtracted using the nearest offset for each, and the 4 sky-subtracted images were aligned, shifted and combined.

This worked well for target MHO 2235-B where the offset between the A and B components was small, but for MHO 2234, where several knots could be aligned in the slit, the A-B offset was large, and each spectrum was extracted and wavelength calibrated separately, and then combined. The IRAF task *apall* was used to extract one-dimensional spectra, and the telluric standard was used as a reference for the trace for the target spectra, since these have no continuum emission. For the knots MHO 2234-D, MHO 2234-A and MHO 2234-I, the B position spectra resulted too noisy, and only the two A-position spectra were combined and used in the analysis.

The target spectra were corrected for telluric features using the IRAF task *telluric* after interpolating over the stellar absorption lines in the telluric standard star spectra (for B2, A1, and A2 dwarfs this concerns Br γ at $2.166 \mu\text{m}$). After division by the telluric standard, the spectra were multiplied by a black-body corresponding to the standard spectral type to correct the spectral slope. We use the narrow-band imaging of the $\text{H}_2 v=1-0 S(1)$ line from epoch 4 and an effective aperture corresponding to the slit aperture to approximately flux calibrate the spectra. The spectral $v=1-0 S(1)$ line flux for MHO 2235-B is thus estimated to be $1.4 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$.

We took argon and xenon arc lamp exposures while pointing to target, but decided to instead use the night sky OH lines at the location of each knot, for a far more precise wavelength calibration. Typically 30 lines were used to fit a wavelength solution, using as reference the OH line list by Oliva et al. (2013). Thus, at the slit position of each knot we extracted the OH line spectrum from the raw images and made individual wavelength solutions. The typical rms in the fit was 0.3 \AA or 4 km s^{-1} . The instrument profile has a gaussian FWHM of 2.3-2.4 pixels, corresponding to 10 \AA or 140 km s^{-1} .

Table 2. Proper motion measurements of the 31 brightest knots in the jets. The J2000 coordinates of the knots are measured in epoch 4 (2013) and are accurate to $\sim 0.06''$. The proper motions (PM_{ij}) are measured in mas/yr for six different base-lines and listed only for PMs larger than 2σ . The sub-indices *ij* give the motion from epoch *i* to epoch *j*, where epoch 1 is 2003, epoch 2 is 2009, epoch 3 is 2011, and epoch 4 is 2013. The proper motion position angles (PA_{ij}) indicate the direction of the motion from epoch *i* to epoch *j* and the angles are measured from North and Eastwards.

NAME	α_4 (2000) hour	δ_4 (2000) deg	PM ₁₂ mas/yr	PA ₁₂ deg	PM ₂₃ mas/yr	PA ₂₃ deg	PM ₁₃ mas/yr	PA ₁₃ deg	PM ₂₄ mas/yr	PA ₂₄ deg	PM ₃₄ mas/yr	PA ₃₄ deg	PM ₁₄ mas/yr	PA ₁₄ deg
MHO	$\pm 0.06''$	$\pm 0.06''$	± 10		± 28		± 7		± 15		± 35		± 6	
2235-M5	18:28:59.296	0:29:13.32			92	340±18					77	170±25		
2235-M4	18:28:59.666	0:29:12.89	36	350±16			39	4±11					22	8±16
2235-M1	18:28:59.730	0:29:10.95												
2235-M2	18:28:59.826	0:29:10.24												
2235-I1	18:29:01.722	0:29:24.28											13	199±26
2235-I2	18:29:01.732	0:29:21.97	24	221±24			23	195±19	68	168±13	108	178±18	37	186±9
2235-I3	18:29:01.746	0:29:26.29	23	324±25	69	89±23	16	32±26					13	341±27
2235-K	18:29:01.953	0:29:04.37	68	306±9			41	300±11	61	158±15	91	164±21	24	273±15
2235-F2	18:29:03.676	0:29:56.20	53	194±11	128	269±13	58	29±7	42	251±21	74	113±26	43	213±8
2235-F1	18:29:03.843	0:29:59.87									79	179±24		
2235-E	18:29:04.928	0:30:15.12	91	235±6	113	164±14	82	214±5	113	198±8	158	228±13	95	218±3
2235-D	18:29:05.406	0:30:21.11	24	162±24	89	36±18	19	83±22			78	178±25	20	127±17
2235-C1	18:29:05.997	0:30:22.06	48	230±12			43	242±10					28	235±13
2235-A1	18:29:06.655	0:30:30.95	34	170±17			28	167±15					27	167±13
2235-A2	18:29:06.761	0:30:34.05												
2235-B	18:29:06.934	0:30:24.77					15	146±27					13	133±26
2234-H8	18:29:07.922	0:30:24.86	33	312±18	67	88±24	17	0±25					18	334±20
2234-H3	18:29:08.153	0:30:31.95	23	212±25	61	136±26	26	175±16					13	167±26
2234-G1	18:29:08.235	0:30:47.98	41	207±14	130	350±13	21	291±20			119	169±17	19	219±19
2234-H1	18:29:08.363	0:30:32.56	51	194±12			42	186±10					36	188±10
2234-H5	18:29:08.469	0:30:39.93												
2234-H2	18:29:08.498	0:30:35.59					16	149±26						
2234-C	18:29:08.609	0:31:13.50	27	5±22	125	189±13			34	186±25	76	12±25		
2234-E	18:29:08.610	0:31:07.55	23	200±25	106	207±15	45	204±10			144	18±14		
2234-H4	18:29:08.610	0:30:38.89	38	214±16	67	90±24	23	175±19	39	92±23			19	173±18
2234-D1+2	18:29:08.810	0:31:08.38	74	168±8	88	183±18	77	173±5					56	167±6
2234-B1	18:29:09.009	0:31:22.08	52	179±11	149	203±11	76	191±6	70	198±13			58	188±6
2234-A1	18:29:09.045	0:31:28.10												
2234-A2	18:29:09.057	0:31:26.64	71	180±8	116	197±14	82	186±5	46	190±19			61	183±6
2234-I1	18:29:09.570	0:32:07.53							37	35±24	70	54±27	19	63±19
2233-N	18:29:11.560	0:31:20.05	23	100±25					36	14±24			21	56±17
2233-P	18:29:12.443	0:31:46.19	23	125±25					57	316±16				

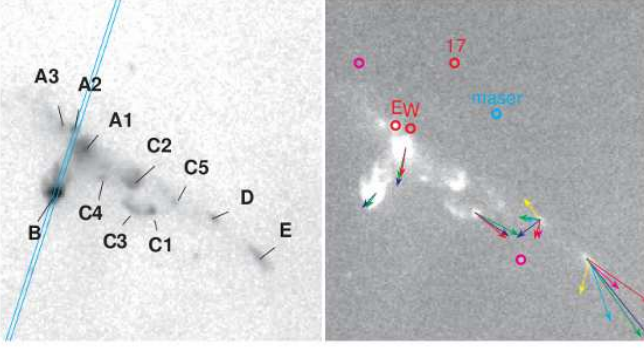


Fig. 4. The central 50'' field comprising the MHO 2235 North-Eastern part. North up, East left. **Left:** Epoch 4 image overlaid with knot identification and slit position for K-band spectroscopy. **Right:** Ep4 image with proper motion vectors, amplified by a factor 20 for clarity. The color coding of the pm vectors is as follows: PM₁₄ (blue), PM₁₂ (red), PM₁₃ (green), PM₂₄ (cyan), PM₂₃ (yellow), PM₃₄ (magenta). Protostars are shown with red circles. Ser-emb-11 E and W (a binary Class I) and Ser-emb-17 are strong candidate driving sources. Magenta coloured circles denote YSO candidates from Harvey et al. (2006). The maser refers to an H₂O maser position from Brand et al. (1994).

3. Identifying the flows kinematically

3.1. Proper motion measurements

We use the four epochs of deep H₂ line imaging from year 2003 (ep1), 2009 (ep2), 2011 (ep3) and 2013 (ep4) to measure proper motions of the knots. Particular attention was paid to the image registration. The combined deep image from each epoch was registered to the reference frame (ep4) using *geomap* and *geotran* in IRAF with a Legendre polynomial of 3rd order and 30-50 reference stars. The rms of the fits were: 0.20 pix for ep1, 0.17 pix for ep2, and 0.23 pix for ep3. After registering ep1, ep2 and ep3 to the same plate scale as ep4, the positional accuracy was again checked by measuring the centroids of all the stars in the field. Figure 3 shows the individual offsets ΔX and ΔY relative to the ep4 X positions. These offsets may include any potential proper motion of the stars, but because we use a large number of stars, we find it appropriate to adopt the average standard deviation as an estimate of the global positional error. The average of all offsets is 0.28 pixels. Excluding the ΔX of ep3, we get an average of 0.26 pixels or 0.06''. This value is used to derive the uncertainty in our proper motion measurements.

We first tried to define the knots' positions and apertures using contours at a 5σ detection level, but due to very different intensity levels and diffuse inter-knot emission, we decided not to use a general signal-to-noise limit for knot definition but identified them by visual inspection, comparing to the deep narrow-band continuum image from 2003, and using the constraint that the peak emission is well above 5σ . In order to determine the knot positions, a Gaussian fit was used to find the central X and Y coordinate for each detected knot in every epoch's deep image. Measurements were done on the registered images, before seeing and flux matching, in order to keep the resolution. For two knots we decided to bin the images in order to derive reliable estimates of the knot centres. The accuracy with which we can determine the knot position varies with each knot, depending on its actual morphology, but we estimate that this centering error in most cases is much smaller than the global positional matching error of 0.26 pixels, which we adopt as our error.

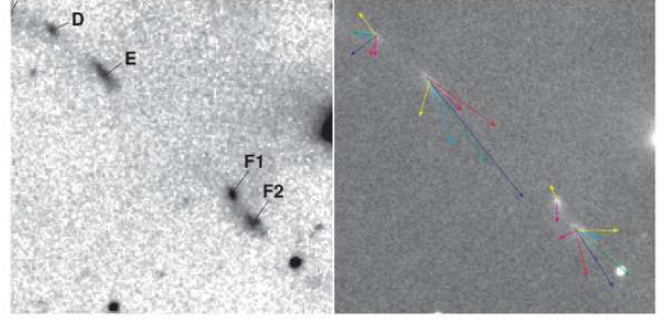


Fig. 5. The 40'' field around the fastest moving knot, MHO 2235-E. See text and the caption of Fig. 4 for details.

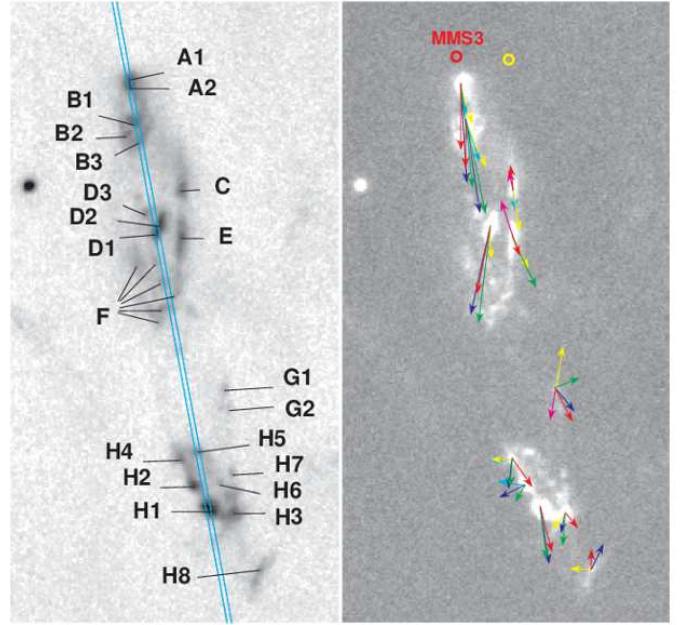


Fig. 6. The southern part of MHO 2234. See text and the caption of Fig. 4 for details. The Class 0 protostar MMS3 (aka Ser-emb-1, red circle) is probably the driving source. The yellow circle shows the location of another red YSO from Harvey & Dunham (2009).

In total we have identified 57 knots, and for 31 of these we can reliably measure the knot positions. These are listed in Table 2. The J2000 positions are given for epoch 4 (2013), using 46 stars from the 2MASS point source catalogue (Skrutskie et al. 2006) to calculate the plate solution with an rms of 0.06'' both in RA and DEC. The proper motions (PM) are calculated in milli arc seconds per year (mas/yr) for each of the six base-lines. The length of the PM vectors are given in Table 2 as PM_{ij}. The base-lines are indicated by the sub-indices *ij*, referring to motion from epoch *i* to epoch *j*. The position angles of the PM vectors are given as PA_{ij}, measured positively from North and Eastwards, from epoch *i* to epoch *j*. The errors in the proper motion speed (in mas/yr) are calculated for each base-line, using the above adopted positional error of 0.26 pixels. The proper motion speed errors are, thus, estimated to be: ePM₁₂=10, ePM₂₃=28, ePM₁₃=7, ePM₂₄=15, ePM₃₄=35, and ePM₁₄=6 mas yr⁻¹. The errors in the position angles of the PM vectors are estimated as $180/\pi \times \text{atan2}(ePM/PM)$. The measurements presented in Table 2 list proper motions whenever larger than 2σ .

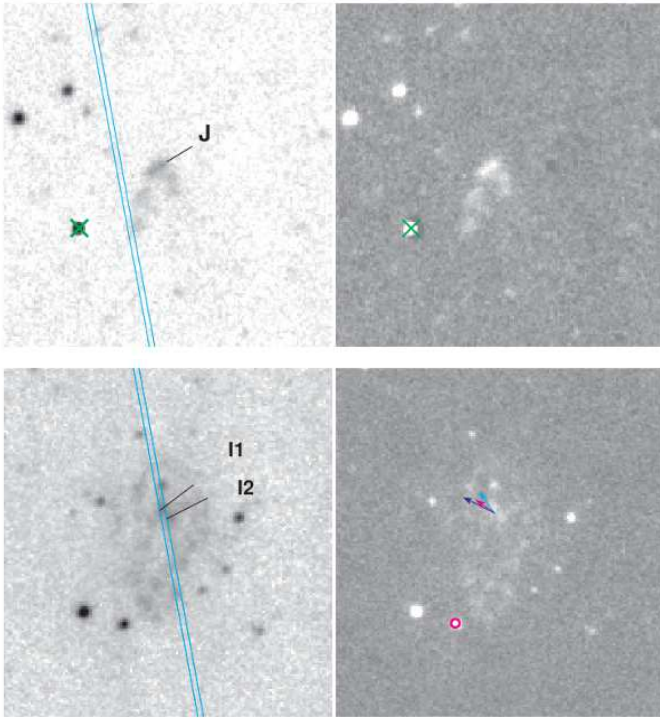


Fig. 7. The northern parts of MHO 2234, lower panels show the field included in the NOTCam monitoring field, while the upper panels show the new knot MHO 2234-J further to the North, imaged only once in 2009. The green cross is an artifact. See text and the caption of Fig. 4 for details.

We note that knot MHO 2234-A1 has emerged over the course of our observations from being hardly noted in epoch 1 to becoming roughly as bright as its close neighbour A2 in epoch 4. No proper motion could be calculated for it.

The multi-epoch proper motion vectors are overlaid in colours on the zoomed images shown in Figs. 4 to 10. Each figure is a zoom-in of a sub-region and shows the H₂ line (+ continuum) image with knot identification and slit position for K-band spectra in the left panel, and the inverse greyscale with the proper motion vectors overlaid in the right panel. The PM vector length is amplified by a factor 20 for clarity, and every base-line is colour coded as explained in the caption of Fig. 4.

Multiple PM vectors for the same knot follow more or less the same direction (approximately within the errors of the position angles), from base-line to base-line, for instance knots A1, B, C1 in Fig. 4, knots A2, B1, D1+D2, H1, in Fig. 6, knot I1 in Fig. 7, and knot M4 in Fig. 10. For several knots, however, there is a large directional scatter, such as for knots D, E, and F2 in Figs. 5, and knots G1, H3, H4, H8, in Fig. 6. In these cases the maximum spread of the multi-epoch vectors for one and the same knot can be 90 degrees or more. Most of these are relatively faint or elongated knots, and it could be that we have underestimated the positional uncertainty due to a more difficult centering. Thus, it is unclear whether this scatter is real or merely reflects a larger measurement error for these knots.

In addition to the PM measurements we made difference images between epochs using the seeing matched and flux matched images. Figure 11 shows part of the southern arm of the MHO 2234 jet, including knots A1, A2, B1, B2, B3, C, D1, D2, E and the F knots (cf. Fig. 6), and Fig. 12 shows the same region as that in Fig. 4. When a knot has moved it shows up as a negative

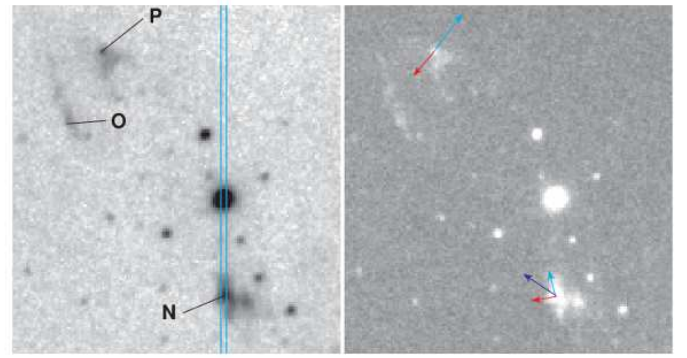


Fig. 8. The north-eastern part of MHO 2233 (37'' field). See text and the caption of Fig. 4 for details.

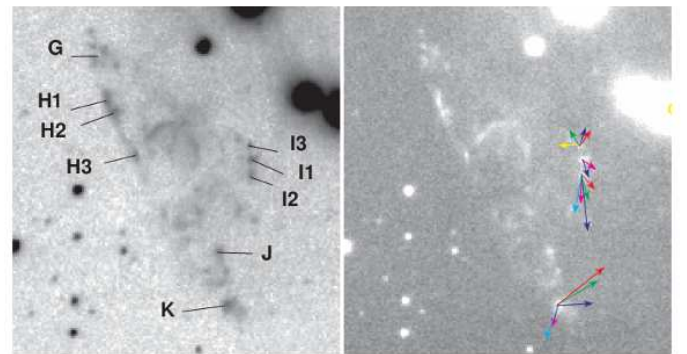


Fig. 9. The South-Western part of MHO 2235 (47'' field). See text and the caption of Fig. 4 for details.

shadow next to a positive peak of emission, although, difference images are also highly sensitive to slight changes in the knot morphology and/or flux. Figure 12 demonstrates the brightening around knot MHO 2235-A1 that appeared some time between 2009 and 2011 and disappeared again some time before the 2013 observations, a clear example of rapid changes in protostellar jets. In general, there is agreement between the PM vectors and the shifts in the difference images.

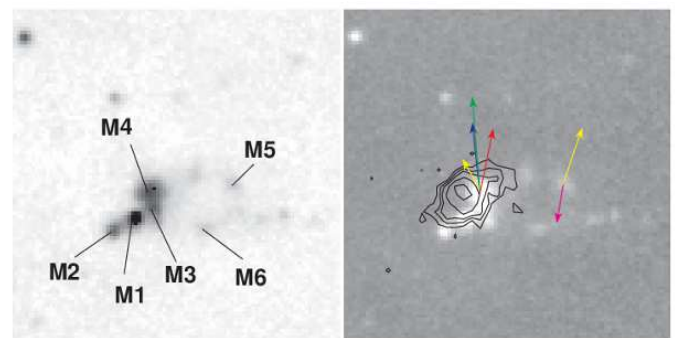


Fig. 10. Zoom in on the HH 476 region (20'' field), the SW part of MHO 2235 in the NOTCam field. See text and the caption of Fig. 4 for details. The black contours show the H α emission from 2009 of the previously known Herbig-Haro object HH 476.

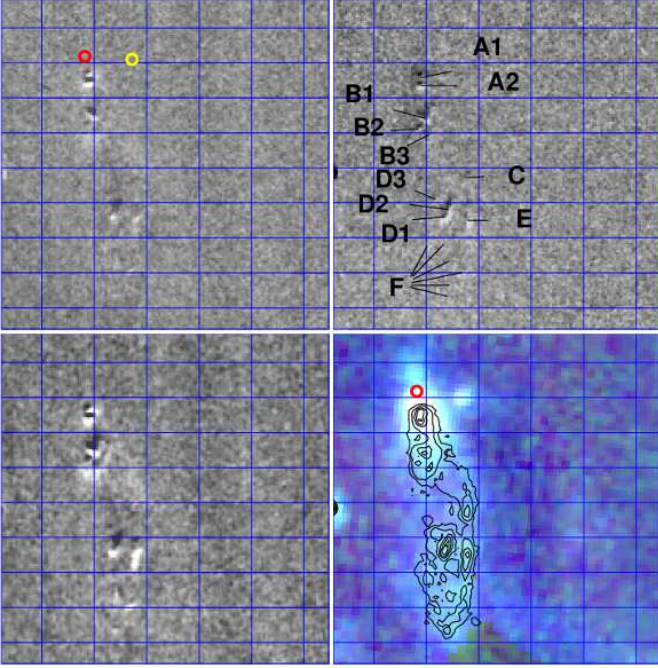


Fig. 11. Difference images for part of the MHO 2234 flow including the position of the Class 0 source MMS3 or Ser-emb-1 (red circle) and a not classified YSO from Harvey & Dunham (2009) (yellow circle). The image shifts are in the sense: ep2-ep1 (upper left), ep3-ep2 (upper right), and ep4-ep1 (lower left), bright regions showing positive flux. The IRAC/Spitzer $4.5 \mu\text{m}$ (blue), $5.8 \mu\text{m}$ (green) and $8 \mu\text{m}$ (red) is shown with the $\text{H}_2 v=1-0 S(1)$ line emission in black contours (lower right).

3.2. Tangential velocities

There has been a discrepancy in the distance estimates to Serpens between the VLBI parallax measurement of EC95 giving a distance of 415 ± 5 pc for the Serpens Main Cluster (Dzib et al. 2010), a neighbouring cloud located $< 1^\circ$ to the north, and extinction studies looking at the global properties of the Serpens–Aquila cloud complex which find smaller distances; 225 ± 55 pc according to Straizys et al. (2003) and 203 ± 7 pc according to Knude (2011). The extinction map of the Serpens–Aquila region shown in Bontemps et al. (2010) and the discussions in Maury et al. (2011) suggest that the Northern part of the complex, comprising Serpens Main and NH3, is a separate entity from the rest of the complex, seen in projection, and located at a larger distance. In this paper we will follow this reasoning and adopt 415 pc as the distance. For the longest base-line of about 10 years, the uncertainty in the tangential velocity is 12 km s^{-1} while for the shortest base-line of less than 2 years, it is 67 km s^{-1} , see Table 3. The highest velocity measured over the longest base-line is 190 km s^{-1} for knot MHO 2235-E, see Fig. 5. This scales down to roughly half the value if we apply the 220 ± 80 pc distance estimate (Straizys et al. 2003).

The highest tangential velocities are found for the four knots MHO 2235-E, MHO 2234-A2, MHO 2234-B1, and MHO 2234-D1+D2, but there is an all over large variation in speed, see Sect. 3.6 for a discussion on time-variable velocities. The median velocities over the longest time-scale of 10 years are about 50 km/s , but the scatter is large, from 30 to 190 km/s . These are based on the measurements of 17 knots only, about $1/3$ of all identified knots, and about 60% of the knots we were able to

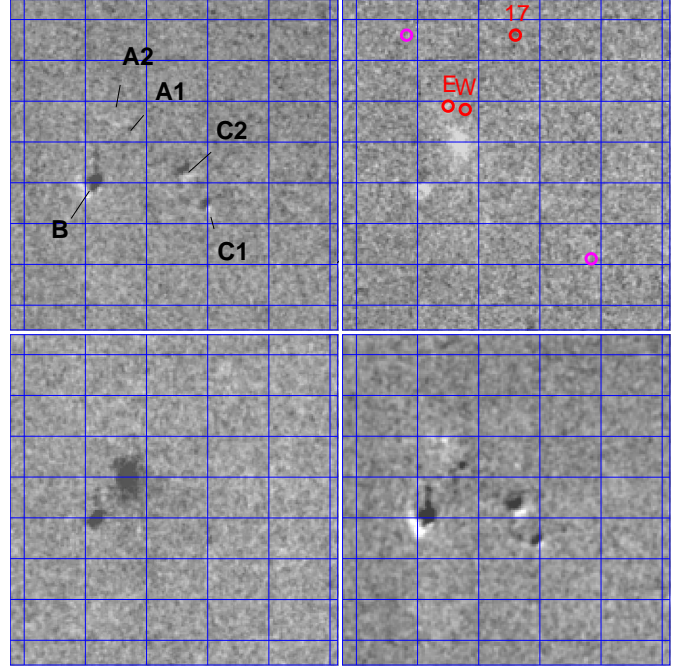


Fig. 12. Difference images for part of the MHO 2235 flow including the position of the Class I sources Ser-emb-17 and Ser-emb-11 E and W (red circles) and two YSO candidates from Harvey et al. (2006) (magenta circles), cf Fig. 4. The image shifts are in the sense: ep2-ep1 (upper left), ep3-ep2 (upper right), ep4-ep3 (lower left) and ep4-ep1 (lower right), bright regions showing positive flux. The brightening near knot A1 appeared in the 2011 image and had disappeared again in the 2013 image.

Table 3. The 6 different base-lines. The first column gives the base-line over years and the second columns shows the sub-indices used, referring to epochs 1, 2, 3, and 4. N denotes the number of knots with proper motions larger than 2σ . The estimated errors in proper motion speed $e\text{PM}_{ij}$ are converted to errors in the tangential velocities (assuming $d=415$ pc).

Base-line	ij	time (yr)	N	$e\text{PM}_{ij}$ (mas/yr)	eV_{tan} (km/s)
2003-2009	12	6.040	21	10	20
2009-2011	23	2.171	14	28	55
2011-2013	34	1.785	10	34	67
2009-2013	24	3.956	11	15	30
2003-2011	13	8.211	19	7	14
2003-2013	14	9.996	17	6	12

measure. Histograms over the velocity distributions are shown in Fig. 13. For the shorter time-scales we are not able to measure the lowest velocities due to the larger error bar, but it is clear that some knots show high velocities over short time-scales, while it averages out over longer time-scales. This is evidence of time-variable velocities showing that knots speed up and brake down.

3.3. $\text{H}_2 v=1-0 S(1)$ line fluxes

For flux measurements, the images are first “seeing matched” using the IRAF task *gauss* which convolves the images with a Gaussian function. All images were matched against the “worst

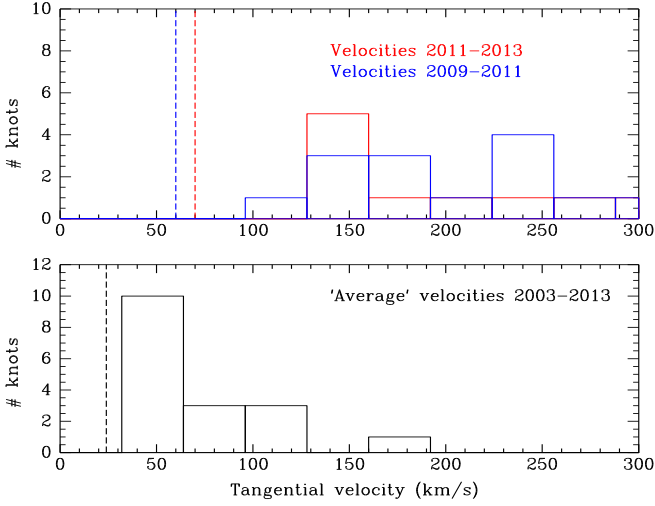


Fig. 13. Number distribution of the measured tangential velocities (in km s^{-1} , assuming $d=415$ pc). The average velocities over a 10 year timespan from 2003 to 2013 (lower panel) are compared to the more “instantaneous” velocities measured over the shortest timescales of about 2 years (upper panel), the 2011-2013 period (bold red) and the 2009-2011 period (blue). Only knots with proper motion velocities above 2σ (vertical dashed lines) are included.

seeing” image using ~ 50 stars. Secondly, “flux matching” with respect to ep4 (2013) was performed using the stellar fluxes. The flux matching error is around 6%, i.e. this is how much the stellar fluxes scatter. We note that many of these stars are Young Stellar Objects (YSOs) currently forming in the region (Djupvik et al. 2006; Harvey et al. 2006, 2007), and YSOs are known to be variable. While a few highly variable stars were discarded before flux matching, low level variability in the stellar sample still might have artificially increased this scatter.

The individual knot fluxes were measured in their apertures using the IRAF task *phot*. The aperture radii varied from 5 pixels ($1.17''$) for the smallest and faintest to 30 pixels ($7''$) for the largest and most diffuse knot, but stayed mostly between 5 and 9 pixels. For elongated knots we used large radii and checked manually that nearby knots did not contaminate the aperture. For each knot the aperture radius was fixed for all epochs, only its position was redefined. The sky annuli were selected depending on the crowding to minimize contamination.

The flux for the same knot is found to be overall fairly constant in all the four epochs, see Table 4. To search for variability we calculate the maximum flux variation, i.e. the difference between the lowest and highest flux measured for the same knot. A knot is defined to have flux variability if the maximum flux deviation is larger than three times the standard deviation of the sky background σ_{sky} in the deep image of ep4, which is $1.5 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$. As shown in Fig. 14 we find flux variability for 13 out of 29 knots. There is no apparent general correlation between flux variability and proper motion.

3.4. Radial velocities

Since the H_2 emission is spatially resolved and the emission lines have narrow essentially Gaussian line profiles, we can use profile fitting to obtain a radial velocity resolution much higher than the intrinsic resolution of the observations of 140 km s^{-1} . For each knot we measure the radial velocities from the available

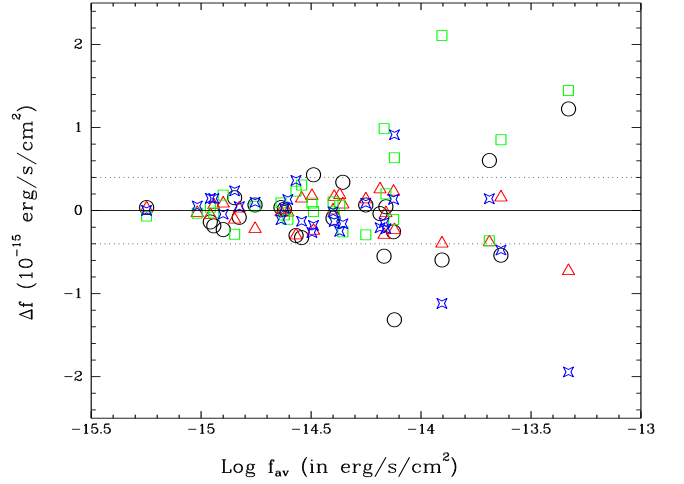


Fig. 14. Flux variability detected in 13 of the 29 knots. The deviations from average flux is plotted versus the logarithm of the average flux for each of the knots. Epoch 1 (black circles), epoch 2 (red triangles), epoch 3 (green squares) and epoch 4 (blue stars). Variability is detected whenever the maximum deviation between epochs is larger than 3σ , where σ is the standard deviation of the sky background in the epoch 4 image. The dotted line shows 3σ from average.

Table 4. The H_2 $v=1-0$ S(1) fluxes of the knots for each of the four epochs. This is the line emission measured through an aperture with radius R_{ap} (in arcseconds) centred on each knot. MHO 2234-A1+A2 comprises both knots although A1 is only clearly emerging in ep4. The fluxes f_1 , f_2 , f_3 , and f_4 are given in units of $10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$. The last column shows whether we find the knot flux to be variable or not.

NAME	f_1	f_2	f_3	f_4	R_{ap} (")	Var
MHO						
2233-N	6.47	6.77		6.30	1.87	y
2233-P	1.41	1.51		1.54	1.40	n
2234-A1+A2	4.75	4.48	4.15	4.25	1.17	y
2234-B1	5.67	5.74	5.32	5.70	1.64	n
2234-C	7.24	7.73	7.39	7.63	2.81	y
2234-D1+D2	21.06	20.08	20.10	20.60	3.28	y
2234-E	6.25	7.33	8.20	8.48	2.34	y
2234-G1	1.03	1.35	1.45	1.22	1.87	n
2234-H1	22.55	23.25	23.94	22.61	2.57	y
2234-H2	6.97	6.89	7.12	6.70	1.87	n
2234-H3	3.89	3.98	4.08	3.96	1.40	n
2234-H4	1.83	1.54	1.81	1.86	1.17	n
2234-H5	2.34	2.29	2.40	2.20	1.40	n
2234-H8	2.54	3.01	3.17	2.73	2.34	y
2235-A1	11.86	12.05	14.56	11.33	2.34	y
2235-A2	2.40	2.40	2.93	3.06	1.40	y
2235-B	48.08	46.13	48.30	44.91	3.74	y
2235-C1	3.67	3.00	3.23	3.06	1.87	y
2235-D	1.57	1.31	1.13	1.66	1.87	y
2235-E	6.24	6.50	7.78	6.64	7.02	y
2235-F1	2.41	2.40	2.34	2.42	1.64	n
2235-I1	0.96	1.05	1.14	1.25	1.17	n
2235-I2	0.96	1.21	1.11	1.29	1.40	n
2235-I3	0.60	0.59	0.50	0.57	1.17	n
2235-K		2.46	2.38	2.61	1.64	n
2235-M1		4.46	4.33	4.02	1.17	n
2235-M2		3.37	3.28	2.93	1.40	n
2235-M4		4.20	4.00	3.90	1.17	n
2235-M5		0.93	0.93	1.01	1.17	n

Table 5. Radial velocities v_{rad} obtained from the available emission lines, corrected for the systemic velocity of the cloud core of $v_{\text{LSR}} = 8 \text{ km s}^{-1}$, and the number of lines used to measure v_{rad} . The tangential velocities v_{tan} are obtained from the proper motion measurements over 10 years and a distance assumption of $d = 415 \text{ pc}$. The space velocities v_{space} are obtained by combining v_{rad} and v_{tan} .

Object	v_{rad} (km s^{-1})	N_{lines}	v_{tan} (km s^{-1})	v_{space} (km s^{-1})
MHO2234-A1+A2*	-32 ± 7	4	121 ± 12	125 ± 14
MHO2234-D1+D2	0 ± 4	4	110 ± 12	110 ± 13
MHO2234-H1	-12 ± 8	4	71 ± 12	72 ± 14
MHO2234-J	16 ± 1	2	n.a.	n.a.
MHO2235-B	5 ± 3	5	26 ± 12	26 ± 12

*) Both knots are included in the slit, but v_{space} is valid only for A2.

H_2 lines using the IRAF tasks *rvidlines* and *rvcorrect* to obtain the local-standard-of-rest radial velocities (v_{LSR}). The accuracy in the wavelength calibration of our spectra is 0.3 \AA or 4 km s^{-1} (see Sect. 2.3), and since the calibration is done on sky lines in the same spectrum we do not expect any shifts. The reference wavelengths for the H_2 lines are taken from the vacuum wavenumbers provided by Black & van Dishoeck (1987). The number of available lines vary from 1 to 6, depending on the brightness of the knots.

The measured radial velocities are very similar for all lines in the same knot. The adopted error listed in Table 5 is taken to be the rms scatter in the radial velocity measurements line-by-line rather than the mean error. The Serpens NH3 NE cloud core itself has a mean radial velocity $v_{\text{LSR}} = 8.5 \text{ km s}^{-1}$ according to Tobin et al. (2011), whose measurement is centered on the Class 0 source MMS3, and 7.986 km s^{-1} according to Levshakov et al. (2013), who refer to this cloud core as Do279P6. We apply 8 km s^{-1} when correcting for the systemic velocity. We assume the protostar that gives rise to the jet follows the cloud motion and thus correct for it to find the knot radial velocity with respect to the driving source. The radial velocities given in Table 7, with their uncertainties and the number of lines used in the measurement, are thus the LSR velocities corrected for the systemic velocity of the cloud.

The negative radial velocities in the southern MHO 2234 jet and the positive radial velocity for one measurable knot in the northern, gives the orientation of the jet along the line of sight. The small number of northern knots detected is likely due to the fact that the northern jet moves away from us and into the cloud. The only northern knot that has measurable radial velocity is MHO 2234-J, a bow shock shaped feature outside our H_2 imaging field, for which we have no proper motion measurements. The knot MHO 2234-A1, for which we have no proper motion because it was too faint in all epochs except for epoch 4, was bright by the time the spectrum was taken and included in the slit, thus its v_{rad} was obtained together with the one of knot A2. These two knots have the largest radial velocity measured. The radial velocity of MHO 2235-B is very small, but positive, thus the spatial velocity of this knot is towards SE and away from us.

3.5. Identification of flows and their driving sources

Combining the tangential velocities derived from the proper motions with the radial velocities, available for a subset of the knots, we obtain the space velocities. We use the space veloci-

Table 6. Driving source candidates. Values of L_{bol} and T_{bol} and estimates of disk masses, as well as positions from CARMA 230 GHz observations are all from Enoch et al. (2009, 2011).

Ser-emb-	α_{2000} (h)	δ_{2000} (deg)	YSO	L_{bol} (L_{\odot})	T_{bol} (K)	M_{disk} (M_{\odot})
1 (MMS3)	18 29 09.09	00 31 30.9	0	4.1	39	0.28
11 E	18 29 06.75	00 30 34.4	I	-	-	-
11 W	18 29 06.61	00 30 34.0	I	4.8	77	0.15
17	18 29 06.20	00 30 43.1	I	3.8	120	0.15

ties, the morphology, and the locations of known protostars listed in Table 6 to evaluate the best candidate driving source for each jet, and also to distinguish between separate jet flows and determine which knots belong to which flow. We find at least three separate jet flows, partly overlapping, in the field of view studied.

It should be noted that there are several emission line features that can not easily be attributed to any of these flows, either because they have no velocity information and/or their location and morphology is difficult to interpret. This concerns in particular the features named Q, R, S, and T in Fig. 2.

3.5.1. Flow 1 and MMS3 (Ser-emb-1)

What we call Flow 1 essentially coincides with the MHO 2234 flow as depicted in Fig. 2. In Djupvik et al. (2006) we suggested the driving source to be the Class 0 source MMS3, also called Ser-emb-1 by Enoch et al. (2009, 2011), who found it to be a single compact source and an early Class 0, probably the least evolved of all protostars in Serpens. From the present study it is confirmed that the jet has a bipolar structure with a southern flow (Fig. 6) coming towards us and a northern (Fig. 7) going away from us. From the spatial velocities of the two knots A2 and H1 in the southern arm we estimate an inclination angle of 10-15 degrees with respect to the plane of the sky. This is in agreement with the VLA velocity maps of Tobin et al. (2011), although their axis of the outflow in the plane of the sky is directly North-South, while both the morphology of the jet, as seen in near and mid IR images, as well as the proper motions of the H_2 knots, indicate a sky position angle of about 10 degrees.

In the southern arm we find a spectacular morphology of at least three main structures, each of which consist of curvy whisps of knots that look like fragmented bow-shocks, headed by the B knots at $\approx 9''$ from the driving source, the F knots at $\approx 35''$ and the H knots at $\approx 60''$. We speculate that these multiple bow shocks are the result of several bursts of outflow along the jet axis in the recent past, produced by a time-variable jet ejection mechanism. We do not see a strong bi-polar symmetry though, probably because the northern arm moves slightly into or behind the cloud and is detected at 2 microns only in two locations; 1) a bubbly and faint multi-knot feature around the I1-2 knots, at ($\approx 37''$) from the exciting source, and 2) the clear bow shock shaped feature named J, which is at $\approx 120''$ from the driving source. In the $4.5\mu\text{m}$ IRAC image, however, there is extended emission right to the north of the exciting source, most likely the northern component of the bipolar flow moving into the cloud, being very reddened (cf. Fig. 11).

From the velocity information we find it likely that the southernmost part of the MHO 2234 jet, containing the H1-H8 knots, is indeed part of the north-south going Flow 1 (MHO 2234), and not part of the MHO 2233 structure. Knot H8 apparently moves in the reverse direction, though.

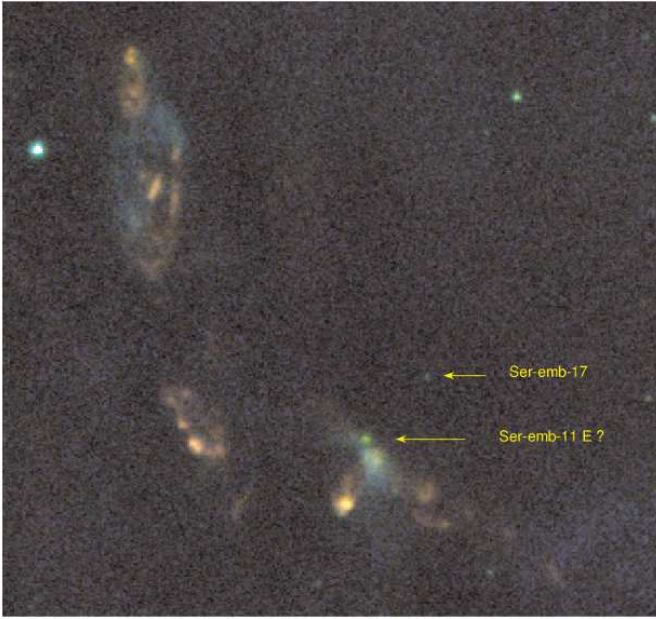


Fig. 15. Central part (FOV $\approx 90''$) of the jets colour coded H₂ line filter (red), K-band filter (green) and H-band (blue). North up, East left.

The space velocity of the knots decreases with distance from the originating source, the faster knot being MHO 2234-A2 at a space velocity of 125 km s^{-1} . Its close neighbour A1 is very faint in ep1, and becomes gradually brighter to allow its position to be measured only in epoch 4, but both A1 and A2 are included in the flux measurement aperture and in the slit spectroscopy. As shown in Sect. 9 where we calculate the dynamical ages, the jet from the least evolved protostar shows higher knot velocities than the jet from the more evolved protostars. This is in line with Bontemps et al. (1996) who found roughly an order of magnitude larger mechanical-to-bolometric luminosity ratio for outflows from Class 0s compared to Class Is.

3.5.2. Flow 2 and Ser-emb-11 binary, E and W

What we call Flow 2 is the longest structure in our $4'$ field of view, a NE-SW oriented flow composed of parts of both MHO 2233 (clearly N and P, and probably O) and MHO 2235 (clearly C1, D, E, F, and probably C2, I1, I2, I3). The previously known HH object HH 476, which practically coincides with our group of M knots, is located at an extension of this line, but the proper motion of knot MHO 2235-M4 has a consistent reverse movement, and it is unclear if this group of knots belong to Flow 2. We also note that the knots MHO 2235-G, H, J and K could be related to Ser-emb-34, in which case it would be a strongly deflected flow, with no detectable counterjet, but this speculation, however, awaits proper motion measurements. As seen in Fig. 1, and also as noted in the MHO Catalogue (Davis et al. 2010), MHO 2235 may be extending further towards the SW far outside the NOTCam field. Whether this is an extension of Flow 2 or an independent flow, is not clear, as we have no velocity information, but no known protostars are found close to these features. The morphology suggests a possible connection, but if both structures to the SW are part of the same flow, this indicates a strong deflection of the jet axis. Thus, Flow 2 could be a parsec scale flow, with parts of it completely

void of emitting knots indicating periods of quiescence in the jet ejection.

Considering the field we have monitored, the knots flowing towards the southwest have very clear proper motions and include MHO 2235-E moving at 190 km s^{-1} , the fastest knot in this study. The flow towards northeast is more difficult to measure, and only MHO 2233-N has a clear proper motion towards the northeast. From the morphology and tangential velocities, we suggest that this flow originates in Ser-emb-11, or in either of the two components of this $2.14''$ separation Class I binary.

Inspecting our supplementary deep JHK_s imaging taken simultaneously with H₂ line imaging and a narrow-band K continuum filter, we find evidence that our knot MHO 2235-A2, which almost coincides with the protostar Ser-emb-11E, indeed has emission both in the red continuum filter, as well as in the H₂ line filter. This source is the eastern and the fainter of the two Class Is that form the 890 AU separation protostar binary Ser-emb-11, which is found by Enoch et al. (2011) to have very extended envelopes and compact disk components. In our images MHO 2235-A2 has a roundish shape, but its psf in the best quality images, where stars have a FWHM of $0.5 - 0.6''$, is substantially broader. The positions disagree by $0.4''$. The binary companion Ser-emb-11W, which is the brighter of the two in submm wavelengths, is not detected in any near-IR filter. We find no measurable proper motion from MHO 2235-A2. On the other hand we detect a gradual brightening in flux over the 10 years of monitoring in the H₂ line filter, see Tables 2 and 4. Thus, what we refer to as knot MHO 2235-A2 may be a mix of continuum emission from the YSO itself (Ser-emb-11E) and some extended line emission.

As shown in Fig. 15 there is a cone of faint emission extending southwards from Ser-emb-11E (at about 5 o'clock) in the K continuum filter and in the H-band. This emission is barely noticeable in the J-band, probably due to high extinction. Such cones of scattered light are usually interpreted as cavities in the envelope carved out by a precessing jet. The part of Flow 2 that we have monitored is a long chain of knots with a slightly S-shaped morphology. This point symmetry is usually interpreted as due to a precessing jet axis. As shown by Fendt & Zinnecker (1998) this is most likely caused by orbital motion of the jet source in a binary (or multiple) system.

3.5.3. Flow 3 and Ser-emb-17

Proper motion and radial velocity data show that MHO 2235-B, the brightest of all knots in the images, is moving towards the South-East and slightly away from us. From the radial velocity component we determine the inclination angle with respect to the plane of the sky to be 11° . Knot MHO 2235-A1 has a similar, within the errors, proper motion vector. These two knots seem to form a separate flow approximately orthogonal to the above described Flow 2. The Class I binary Ser-emb-11 is situated approximately where the two flows cross each other in the plane of the sky. Thus, it is likely that the south-east going Flow 3 is either driven by one of the components of the Class I binary Ser-emb-11 or by Ser-emb-17, the proper motion vectors being consistent with both. The Class I source Ser-emb-17 (Enoch et al. 2009, 2011) is located only $12''$ to the North-West of the binary Ser-emb-11 and is detected as a faint point-source in the K-continuum and the K_s broad band filters only, see Fig. 15. Careful inspection of the IRAC image in Fig. 16 reveals a *bridge* of H₂ emission (green colour gives an emphasis to the 4.5 micron band) between Ser-emb-17 and Ser-emb-11, suggesting a flow in the direction towards MHO 2235-B. The non-detection of this

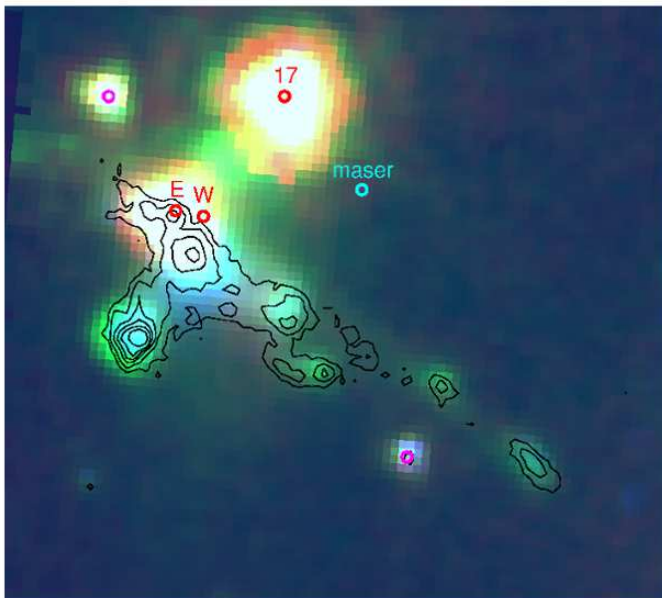


Fig. 16. The central $\approx 45''$ zoom-in of IRAC/Spitzer image shown in Fig. 1. Protostars are marked and labelled. The black contours refer to the $2.1218 \mu\text{m}$ H_2 line emission.

extended emission at two microns is probably due to very high extinction. Ser-em-17 is located in the densest core in the region according to the N_2H^+ map of Tobin et al. (2011). Extinction may also explain why we detect no bipolar lobe towards the north-west. Based on this and the morphology and velocity of MHO 2235-B, we propose Ser-emb-17 to be the driving source of the south-east flowing jet.

Based on jet lengths only, one would wrongly interpret Flow 3 as the youngest jet in the region. Including the velocity information, however, we find that the furthest away knots in the longer Flow 1 from the Class 0 source has approximately the same dynamical age, see Sect 9. A recent study by Giannini et al. (2013) finds a clear correlation of jet length with stellar age, but there were no Class 0 YSOs in their sample of driving sources.

3.6. Time variable velocities

It is evident from the multi-epoch proper motion results presented in Table 2 that the proper motions are not constant over time. Translated to tangential velocities using 415 pc for the distance, the most typical velocity, averaged over 10 years, is around 50 km/s, and the highest velocity is 190 km/s as shown in Fig. 13, but short-term proper motions over ~ 2 years reveal “transient” velocities of up to 300 km/s, for instance MHO 2234-B1 from 2009 to 2011 and MHO 2235-E from 2011 to 2013. These are knots that have speeded up but move in the same direction as for the other periods. Thus, the H_2 knots accelerate and decelerate.

The observable knots are shocks, probably produced by supersonic velocity jumps, for which a natural origin is believed to be a time variable jet ejection speed. Episodically pulsed jets, due to non-steady accretion in the form of bursts, was suggested as an explanation of knotty jet structures by Reipurth (1989), and modeled by (Raga et al. 1990), and strong evidence for this mechanism was found in the highly symmetric knots in the HH 212 bipolar jet (Zinnecker et al. 1998). The morphology and the knot spacings indirectly point towards time-

variable velocities. Direct measurements of time-variability in jet velocities, however, are scarce. This has been detected from multi epoch studies of a Class II jet in HH 30 (Hartigan & Morse 2007), a Class I binary jet in the L1551 (Bonito et al. 2008), and Class II and Class I jets in the Chamaeleon II star formation region (Caratti o Garatti et al. 2009). It is suggested that Class 0 jets have a similar variability behaviour, based on observed knot spacings, but to our knowledge, the present study in Serpens is the first that finds time-variable velocities in a Class 0 jet.

Ejecta at different velocities propagating in a strongly inhomogeneous medium give rise to rather complex interactions and possibly deflections. The jets in Serpens NH3 (Serpens Cluster B) are partly overlapping, and it is not simple to interpret which knot belongs to which flow, considering reverse motion and deflections.

It is believed that faster ejecta may overtake slower ones, and potentially change their velocity vectors. Models of randomly pulsed jets by Bonito et al. (2010) predict: distinct individual knot velocities, single fast-moving knots, reverse shocks, as well as oblique shocks, the latter being produced by reflection at the cocoon surrounding the jet. Our velocity data for the knots in these jets suggest the presence of several of these features. The distinct individual knot velocities are clearly demonstrated by our proper motion results. An example of a single fast-moving knot is MHO 2235-E. Possible examples of reversing knots are MHO 2235-M4 and MHO 2234-H8.

Whether a variable jet ejection mechanism is needed to produce the observed time variability in the knot velocities is not entirely clear, and Yirak et al. (2009, 2012) suggest that shocks can be produced by clumps in the jet that collide and merge. If the shocks are due to merging or interacting knots, one would expect variability in the fluxes, as well. The fast moving elongated knot MHO 2235-E experiences both velocity and flux variability, but in general we find no clear correlation between flux variability and velocity variability, nor between flux variability and speed.

4. Physical conditions

The knots for which we have K-band spectra are listed with their line fluxes or flux ratios in Table 7. The slit positions are shown overlaid on images in Figs. 4, 6, 7 and 8. All the knots have pure emission line spectra with narrow line profiles, the gaussian widths being of the order of the instrument profile, around 10 \AA or 140 km s^{-1} . Up to six or seven H_2 lines are typically detected in the spectra. There are no other lines, nor continuum emission. Figure 17 shows knot MHO 2235-B as an example. For all knots the brightest line is the $v=1-0 \text{ S}(1)$ line at $2.1218 \mu\text{m}$ which contributes on the average $59 \pm 17 \%$ of the total emission in the K band.

4.1. Extinction

There is substantial cloud extinction in the Serpens NH3 core where these jets are located, and the region is practically opaque in the optical. Even in the K-band there is a pronounced decrease in the number of background stars over the region where the jets are located. A lower estimate of $A_V \sim 20 \text{ mag}$ was deduced from the $J-H/H-K$ colour diagram of stars in the surrounding region (Djupvik et al. 2006), which agrees well with the extinction map of Bontemps et al. (2010), but these methods “saturate” for the densest regions. There is no emission from the knots in the J and H bands. Deep H band imaging shows some faint extended

Table 7. Measured H_2 line fluxes and line ratios. The flux density (in $\text{erg s}^{-1} \text{cm}^{-2}$) is given for the $v=1-0$ S(1) line at $2.1218 \mu\text{m}$, and flux ratios with respect to this line are given for the other lines. The third last column gives the estimated excitation temperatures T_{ex} , the second last gives the estimated extinction (A_V), and the last column gives the calculated ortho to para ratio o/p for the $v=1$ vibrational level.

Object	1-0 S(1) 2.1218 μm $\text{erg s}^{-1} \text{cm}^{-2}$	1-0 S(2) 2.0338 μm ratio	2-1 S(3) 2.0735 μm ratio	2-1 S(2) 2.1542 μm ratio	1-0 S(0) 2.2233 μm ratio	2-1 S(1) 2.2477 μm ratio	T_{ex} K	A_V mag	o/p
MHO 2235-B	$1.4 \cdot 10^{-14}$	0.32 ± 0.02	0.10 ± 0.03	0.06 ± 0.07	0.26 ± 0.02	0.13 ± 0.04	2240 ± 160	23	2.9
MHO 2234-A1+A2	$4.4 \cdot 10^{-15}$	0.23 ± 0.04	0.04 ± 0.20	-	0.30 ± 0.05	0.14 ± 0.07	1800 ± 310	58	3.2
MHO 2234-D1+D2	$5.9 \cdot 10^{-15}$	0.27 ± 0.04	0.12 ± 0.07	-	0.19 ± 0.06	0.19 ± 0.05	2500 ± 300	14	3.7
MHO 2234-H1	$5.6 \cdot 10^{-15}$	0.22 ± 0.07	0.04 ± 0.09	0.04 ± 0.12	0.19 ± 0.06	0.06 ± 0.11	1900 ± 170	31	4.1
MHO 2234-J	$1.3 \cdot 10^{-15}$	-	-	-	-	0.36 ± 0.20	-	-	-
MHO 2233-N	$3.3 \cdot 10^{-15}$	0.35 ± 0.05	0.16 ± 0.10	0.07 ± 0.19	0.23 ± 0.10	0.20 ± 0.11	2620 ± 160	7	3.0

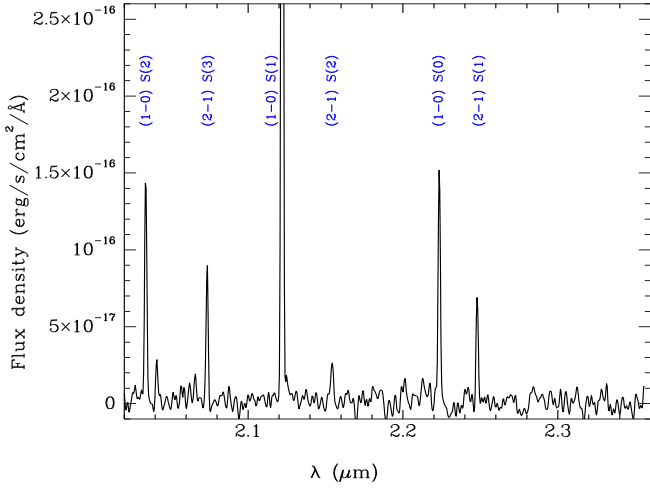


Fig. 17. NOTCam K-band ($R=2100$) spectrum (slightly smoothed) of the brightest knot MHO 2235-B with the H_2 lines marked. Flux density in units of $\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$.

emission between some the knots, which we interpret as due to scattered light.

Assuming thermalized gas at a single temperature, we can use the pair of lines originating from the same upper level that are most separated in wavelength, $\lambda\lambda$ 2.0338 and 2.2233 μm , in order to determine the colour excess between these two wavelengths. We then apply the extinction law $A_\lambda \propto \lambda^{-1.7}$ to deduce the extinction in terms of visual magnitudes. We have in this manner estimated the extinction to the knots (Table 7) to be in the range $7 < A_V < 58$ magnitudes. These values are obtained over a small wavelength range, however, and their uncertainty may be large. The highest estimate ($A_V = 58$ mag) was found for the knot closest to the Class 0 exciting source. Such high values are rarely found in the literature, and above all difficult to measure. Davis et al. (2011) compared various techniques to measure the extinction towards molecular hydrogen emission line regions around protostars using integral field spectroscopy and found values reaching up to $A_V \sim 80$ mag close to the protostellar jet sources. In another study of knots from protostellar jets by Caratti o Garatti et al. (2015) an extinction of $A_V = 50$ mag is reported for one of the knots. Knot emission seen through 50 visual magnitudes of extinction (~ 5 magnitudes at two microns) is weakened by a factor of 100 and must be intrinsically bright.

With this high extinction, one could expect that some knots would be extinguished at 2.1 μm microns, but become ob-

servable at 4.5 μm where the extinction is lower, for instance Flaherty et al. (2007) find that $A_{[4.5]} = 0.53 A_K$. When comparing the areas covered by H_2 line imaging with the IRAC images, we conclude that practically all knots found in the mid-IR images are also visible in the near-IR 2.122 μm images, except for two important cases where we believe the extinction is very high: 1) just to the north of the Class 0 exciting source and 2) between MHO2235-B and its presumably driving source Seremb-17. Otherwise, the practically one-to-one correspondence between IRAC and ground-based 2.122 μm images, is also in line with what Giannini et al. (2013) finds for the Vela-D molecular cloud, and this suggests that even for relatively high extinction regions, such as in Serpens NH3, near-IR H_2 line mapping is able to pick up most of these emission line objects.

4.2. Excitation mechanism

The excitation mechanism of H_2 in molecular jets from young stars is mainly due to collisions with other H_2 molecules or with H atoms, where typically the lower vibrational levels of the molecule in its ground state get populated. If UV photons are present, however, also the higher vibrational levels can be populated through radiation pumping of H_2 into a higher electronic state, followed by a subsequent decay that populates all the vibrational levels of the ground state. A frequently used rule of thumb is that when the ratio $v = 2 - 1 S(1)/v = 1 - 0 S(1)$ ($2.1477/2.1218$) is $\lesssim 1/10$ and there is an absence of $v \geq 3$ lines, the excitation mechanism of H_2 is from collisions in a hot gas (Wolfire & Konigl 1991), i.e. due to shocks.

In order to estimate the excitation temperature and the column densities of H_2 in the knots, we construct the Boltzmann diagrams as described in Nisini (2008), where we depart from the Boltzmann distribution that describes a gas in thermal equilibrium

$$\frac{N(v, J)}{N(H_2)} = \frac{g_{v, J}}{Z(T)} e^{-E(v, J)/kT_{ex}} \quad (1)$$

to get that the natural logarithm of $N(v, J)/g_{v, J}$, where $g_{v, J}$ are the statistical weights from the selection rules of the transitions, equals $-E(v, J)/kT_{ex}$. Thus, when plotting $\ln(N(v, J)/g_{v, J})$ versus $E(v, J)$, a thermalized gas will give a linear relation, where the slope is the inverse of the excitation temperature T_{ex} . $Z(T)$ is the partition function, and the rovibrational energies $E(v, J)$ are taken from Dabrowski (1984). To calculate the relative column densities $N(v, J)$ for a given vibrational and rotational level (v, J) , we use the relation $N(v, J) = 4\pi I(v, J)/(h\nu g(v, J)A(v, J)$, where $I(v, J)$ are the measured line intensities obtained from the line fluxes given in Table 7, corrected

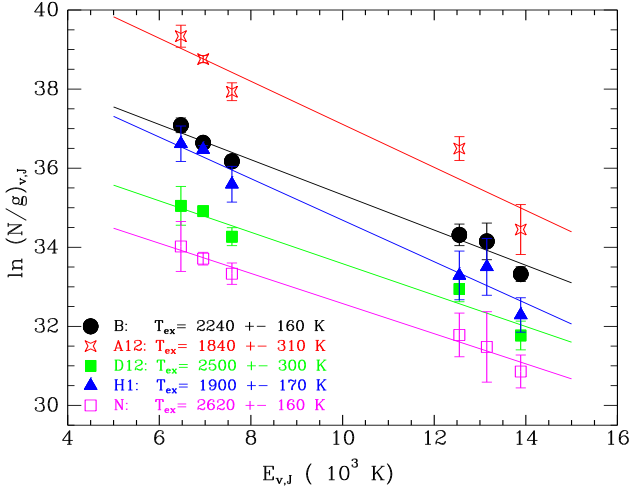


Fig. 18. Excitation diagram for the knots listed in Table 7. The entries for each knot are marked with different symbols and colours and are calculated from the de-reddened line intensities in units of $\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ according to the relation given in the text. Linear fits are made to the points for each knot. Column densities $N(v, J)$ are in the units of cm^{-2} .

for extinction using the derived extinction for each knot, and given in units of $\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1}$ using that the spectra cover an area of $0.6'' \times 1.9''$ across each source. The Einstein coefficients $A_{v,J}$ are from Turner et al. (1977). We fitted a line through the points for each knot, as shown in Fig. 18 and the resulting T_{ex} values and errors are listed in Table 7. Since both the $v = 1$ and $v = 2$ vibration levels can be fitted with the same slope, this suggests that the gas is in LTE and the excitation mechanism is through collisions. The average excitation temperature T_{ex} is 2200 ± 350 K, which is within the typical range of gas temperatures in post-shock regions of protostellar jets (2000-4000 K).

4.3. Ortho to para ratio

When H_2 molecules are formed, their nuclear spins can either be aligned (ortho) or opposed (para). The ortho to para ratio of H_2 , referring to these two possible spin states, has been estimated for the vibrationally excited state $v=1$ using the line ratios $v=1-0 \text{ S}(1)/v=1-0 \text{ S}(0)$ and $v=1-0 \text{ S}(1)/v=1-0 \text{ S}(2)$ following the method of Smith et al. (1997). For each knot we applied the individual extinction estimates as found above, though extinction has marginal effect on the results. Our values for the ortho to para ratios are listed in Table 7 and vary from 2.9 to 4.1 with an average value of 3.3, which is consistent with the expected ratio of 3:1 based on the statistical weights. This very ratio is found in many regions of Herbig-Haro flows. The interpretation could be either 1) that the molecules formed on grains at high temperature according to the statistical weights, and there has been no conversion since, or 2) that collisions with H atoms in the shocked gas has thermalized the level populations and produced this ratio. According to Smith et al. (1997) the latter is the more likely explanation.

4.4. H_2 column densities

For the five knots that have spectra taken, we derive the column densities of H_2 from the already constructed Boltzmann diagram in Fig. 18. We obtained the values of $\ln(N_{\text{H}_2}/Z(T))$ by reading off

the intercept of each slope at zero $E_{v,J}$. The partition function of molecular hydrogen was calculated as $Z(T) = 0.024T_{\text{ex}}/(1 - e^{-6000./T_{\text{ex}}})$ as given in Smith & Mac Low (1997).

For the remaining knots we have no spectra and are limited to flux measurements obtained from H_2 narrowband imaging in the $\lambda = 2.1218 \mu\text{m}$ line. We follow the method of Davis et al. (2001) consisting in using this line intensity together with an assumption on the excitation temperature and the extinction for each knot. We use the average of the four flux measurements given in Table 4. The excitation temperature varies from 1800 to 2620 K among the five knots studied with spectra, and we apply the average value of $T_{\text{ex}} = 2200$ K for all other knots. The extinction apparently varies strongly on small spatial scales and will be the main source of uncertainty using this method. We have estimated the extinction for each knot from a rough spatial interpolation relative to positions for which A_V is already measured with spectroscopy as described in Sect. 4.1. This is the best we can do with the available data, and we caution that an error of 10 magnitudes in the extinction estimate would lead to an uncertainty factor of 2.8 in the dereddened line intensities and subsequently in the column densities and the luminosities.

The surface area for each knot was estimated individually due to their different morphology, and for this we use the deep image from epoch 4. After having subtracted a smoothed version, using a 13×13 pixel median of the image, for each knot we count those pixels which have fluxes above $3.4 \times 10^{-16} \text{ erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$, which is 2.3 times the standard deviation of the background. The resulting surface areas for the 29 knots are in the range 1.3 to 10.9 square arc seconds, translating to the range from 5×10^{31} to $4 \times 10^{32} \text{ cm}^2$ at 415 pc distance, with a median value at $1.3 \times 10^{32} \text{ cm}^2$.

We now have dereddened intensities per steradian in the $v=1-0 \text{ S}(1)$ line, which is used to calculate the column densities as described in Davis et al. (2001). These are listed in Table 8 in units of H_2 molecules per cm^{-2} . The knots are grouped by flows, the first block containing the Flow 1 knots, the second block the Flow 2 knots, and the third block the Flow 3 knots. For the purpose of comparison we list the results obtained by both methods for those five knots that have spectra, marking the results from spectra with an asterisk. The N_{H_2} obtained from imaging compare reasonably well to the more accurate estimates from spectroscopy, the column densities are typically within a factor of 2-3, except for knot MHO 2234-A1+A2 where they differ by a factor of five. Thus, the results for knots where we have no spectra, should be regarded as approximate and accurate only to within an order of magnitude. The H_2 column densities listed in Table 8 compare well with the range of values found in similar studies of knots in protostellar flows. Caratti o Garatti et al. (2015) found H_2 column densities from 10^{17} to $2 \times 10^{20} \text{ cm}^{-2}$ for a sample of 65 knots in flows around 14 sources.

The number densities of molecular hydrogen, n_{H_2} , are estimated from the column densities by assuming that the knots' dimension in the radial direction is equal to their narrowest side seen in the images and measured to be on the average $1.4''$. The knots typically have an elongated shape, mainly along the flow direction, which is roughly the orientation of the slits, as well. As learned from the relatively small radial velocities, these jets are flowing practically in the plane of the sky. Thus, applying $1.4''$ translates to a jet diameter of 580 AU. The derived densities n_{H_2} for each knot are in the range 30 - 17000 cm^{-3} , with a median value around 400 cm^{-3} . These densities are very low and indicate either that a small percentage of the jet is molecular, or that the jets are lighter than the ambient medium.

Table 8. Molecular hydrogen column densities as measured using K-band spectra (5 knots) and narrow-band H₂ line imaging (29 knots). The masses are obtained from the column densities N_{H₂} and the surface areas of the knots. The mass-loss rates are estimated using the velocity information of the knots and their location relative to the driving source.

Knot	N _{H₂} (cm ⁻²)	M _{H₂} (M _⊙)	$\dot{M}_{\text{out}}(\text{H}_2)$ (M _⊙ yr ⁻¹)	n _{H₂} (cm ⁻³)
MHO				
2234-A1+A2*	1.5 × 10 ²⁰ (2.8 × 10 ¹⁹)	7.0 × 10 ⁻⁵ (1.3 × 10 ⁻⁵)	9.6 × 10 ⁻⁷ (1.9 × 10 ⁻⁷)	16900 (3200)
2234-B1	2.2 × 10 ¹⁹	7.0 × 10 ⁻⁶	4.7 × 10 ⁻⁸	2500
2234-C	3.7 × 10 ¹⁸	1.1 × 10 ⁻⁶	1.6 × 10 ⁻⁹	4300
2234-D1+D2*	1.4 × 10 ¹⁸ (1.2 × 10 ¹⁸)	6.4 × 10 ⁻⁷ (5.6 × 10 ⁻⁷)	1.5 × 10 ⁻⁹ (1.4 × 10 ⁻⁹)	200 (100)
2234-E	5.2 × 10 ¹⁷	2.1 × 10 ⁻⁷	3.9 × 10 ⁻¹⁰	60
2234-G1	7.7 × 10 ¹⁷	6.6 × 10 ⁻⁸	2.8 × 10 ⁻¹¹	90
2234-H1*	1.1 × 10 ¹⁹ (8.4 × 10 ¹⁸)	5.0 × 10 ⁻⁶ (3.9 × 10 ⁻⁶)	3.0 × 10 ⁻⁹ (2.4 × 10 ⁻⁹)	1300 (1000)
2234-H2	3.6 × 10 ¹⁸	1.0 × 10 ⁻⁶	3.0 × 10 ⁻¹⁰	400
2234-H3	2.4 × 10 ¹⁸	6.0 × 10 ⁻⁷	2.6 × 10 ⁻¹⁰	300
2234-H4	1.4 × 10 ¹⁸	2.6 × 10 ⁻⁷	9.7 × 10 ⁻¹¹	200
2234-H5	2.3 × 10 ¹⁸	3.5 × 10 ⁻⁷	3.4 × 10 ⁻¹¹	300
2234-H8	2.1 × 10 ¹⁸	4.3 × 10 ⁻⁷	1.1 × 10 ⁻¹⁰	300
2233-N*	4.4 × 10 ¹⁷ (1.6 × 10 ¹⁷)	2.3 × 10 ⁻⁷ (8.5 × 10 ⁻⁸)	5.7 × 10 ⁻¹¹ (2.1 × 10 ⁻¹¹)	50 (20)
2233-P	9.2 × 10 ¹⁶	2.0 × 10 ⁻⁸	4.0 × 10 ⁻¹²	10
2235-A2	9.9 × 10 ¹⁷	1.4 × 10 ⁻⁷	8.1 × 10 ⁻¹¹	100
2235-C1	1.1 × 10 ¹⁸	1.7 × 10 ⁻⁷	3.0 × 10 ⁻¹⁰	100
2235-D	6.1 × 10 ¹⁷	7.4 × 10 ⁻⁸	6.5 × 10 ⁻¹¹	70
2235-E	1.4 × 10 ¹⁸	3.5 × 10 ⁻⁷	1.0 × 10 ⁻⁹	200
2235-F1	9.0 × 10 ¹⁷	1.2 × 10 ⁻⁷	1.8 × 10 ⁻¹⁰	100
2235-I1	5.2 × 10 ¹⁷	5.7 × 10 ⁻⁸	7.4 × 10 ⁻¹²	60
2235-I2	5.6 × 10 ¹⁷	5.9 × 10 ⁻⁸	2.2 × 10 ⁻¹¹	60
2235-I3	3.0 × 10 ¹⁷	2.9 × 10 ⁻⁸	6.7 × 10 ⁻¹²	30
2235-K	8.1 × 10 ¹⁷	1.3 × 10 ⁻⁷	2.7 × 10 ⁻¹¹	90
2235-M1	8.5 × 10 ¹⁷	2.2 × 10 ⁻⁷	5.1 × 10 ⁻¹²	100
2235-M2	7.3 × 10 ¹⁷	1.7 × 10 ⁻⁷	1.1 × 10 ⁻¹¹	80
2235-M4	7.4 × 10 ¹⁷	2.1 × 10 ⁻⁷	3.6 × 10 ⁻¹¹	90
2235-M5	4.9 × 10 ¹⁷	5.0 × 10 ⁻⁸	2.8 × 10 ⁻¹¹	60
2235-A1	1.3 × 10 ¹⁸	6.5 × 10 ⁻⁷	1.2 × 10 ⁻⁹	200
2235-B*	1.1 × 10 ¹⁹ (4.8 × 10 ¹⁸)	8.0 × 10 ⁻⁶ (3.4 × 10 ⁻⁶)	4.8 × 10 ⁻⁹ (2.1 × 10 ⁻⁹)	1300 (600)

* Measurements using the spectroscopic data. In parenthesis below are given the values obtained on the same knot using the 2.1218 μm imaging method.

4.5. Dynamical ages

On the assumption that velocities are constant, one can calculate the time it has taken for (a part of) a jet to move to its current displacement from the originating source by dividing jet length by velocity. This represents a dynamical age for the observed feature. In the case that velocities slow down with time, the ages are upper limits. We take the jet lengths to be the straight line projections from knot to driving source, corrected for line of sight inclinations, but not for any possible deflections. We use the average tangential velocities over 10 years coupled with the radial velocities (whenever measurements exist) to get an approximation of the current space velocities of the various parts of the jets. Where we have no radial velocity information, we use the projected length. Table 9 lists our dynamical age estimates for a few features in each of the three flows and demonstrates how recent the jet activity in this region is.

Table 9. Dynamical ages of the knots based on their jet lengths, i.e. separation from the candidate driving source, and their current velocities, v, where we adopt the space velocities when available, and otherwise the tangential velocities over the longest time-scale available. The flow for each knot is given in column 2.

Knot	F	Driving YSO candidate	Length (pc)	v (km/s)	τ _{dyn} (yrs)
MHO 2234-A2	1	MMS3	0.009	125	70
MHO 2234-B1	1		0.019	116	160
MHO 2234-D1+D2	1		0.048	110	420
MHO 2234-H1	1		0.123	72	1680
MHO 2234-I1	1		0.078	40	1900
MHO 2233-N	2	Ser-emb-11	0.174	42	4050
MHO 2235-I2	2		0.208	74	2750
MHO 2235-M4	2		0.264	44	5860
MHO 2235-A1	3	Ser-emb-17	0.028	54	507
MHO 2235-B	3		0.044	26	1650

4.6. Mass loss rates

From the column densities, N_{H₂}, we can estimate the mass of the H₂ gas involved in the emission through the relation

$$M_{\text{H}_2} = 2\mu m_{\text{H}} N_{\text{H}_2} a_{\text{knot}}, \quad (2)$$

where μ is the mean atomic weight, m_H the proton weight, and a_{knot} the area of the emitting region (Nisini et al. 2005). The slit width is substantially narrower than the FWHM of the intensity profiles across the knots. We assume that the knots emit uniformly over their entire surface and use the surface areas derived for each knot as described in the previous section. Thus, we arrive at H₂ gas masses in the range from 2 × 10⁻⁸ to 7 × 10⁻⁵ M_⊙ for the knots (see Table 8). The total mass of H₂ gas in each flow is obtained by summing up all the measured knots and listed in Table 10. These estimates are a lower limit to the total H₂ gas mass. There are a number of weaker knots for which we do not have reliable flux measurements. It is clear, however, that there is an order of magnitude more mass in the H₂ knots of the Class 0 jet (Flow 1) compared to the two Class I jets.

To estimate the H₂ mass-loss rates we use the dynamical age, t_{dyn}, derived from the spatial velocities and the separation of each knot to its putative driving source in Table 9 and find per knot $\dot{M}_{\text{out}}(\text{H}_2) = M_{\text{H}_2}/t_{\text{dyn}}$. For the 24 knots where we have no radial velocity, we have used the average tangential velocities, which for all jets are the dominating vectors of the space velocities, as these are all flowing practically in the plane of the sky. In this way we obtain the mass-flux carried by each knot. As shown in Table 8 the derived mass loss rates per knot are in the range $4 \times 10^{-12} \text{ M}_{\odot} \text{ yr}^{-1} < \dot{M}_{\text{out}}(\text{H}_2) < 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$. Except for the lowest rates, these values compare well with the mass flow rates estimated for knots in HH 52, HH 53 and HH 54 (Caratti o Garatti et al. 2009). They also compare well to the mass loss rates of 6×10^{-10} to $2 \times 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$ obtained for 9 embedded Class I outflow sources by Davis et al. (2001) although these values are derived in the vicinity of the driving sources. Likewise, Caratti o Garatti et al. (2012) find an average $\dot{M}_{\text{out}}(\text{H}_2)$ of $3.4 \times 10^{-9} \text{ M}_{\odot} \text{ yr}^{-1}$ for five Class Is and six very young YSOs. We have summed up individual knot values to arrive at total values for each flow in Table 10.

The derived mass loss rate is two to three orders of magnitude larger for the Class 0 jet (Flow 1) than for the two Class I jets. This is a combination of the higher mass in the ejecta and the higher knot velocities measured for the Class 0 jet. The

Table 10. Estimates of total H_2 luminosity, mass, mass flow rate and momentum flux in each flow, as obtained by summing over the individual knots. L_{bol} of the driving source are from Enoch et al. (2009, 2011).

Flow	L_{bol} (L_{\odot})	L_{H_2} (L_{\odot})	M_{H_2} (M_{\odot})	\dot{M}_{out} ($M_{\odot} \text{ yr}^{-1}$)	\dot{P}_{H_2} ($M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$)
1	4.1	0.3	8.7×10^{-5}	1.0×10^{-6}	1.3×10^{-4}
2	4.8	0.02	2.0×10^{-6}	2.0×10^{-9}	2.6×10^{-7}
3	3.8	0.04	8.6×10^{-6}	3.3×10^{-9}	1.9×10^{-7}

momentum flux $\dot{P} = \dot{M}v_{\text{space}}$ for the Class 0 jet (Flow 1) is $1.3 \times 10^{-4} M_{\odot} \text{ km s}^{-1} \text{ yr}^{-1}$, which is almost 3 orders of magnitude larger than the momentum flux in the Class I jets. We note that the three driving sources have a similar bolometric luminosity $L_{\text{bol}} \sim 4L_{\odot}$ (Enoch et al. 2011). Thus, among three YSOs with a similar L_{bol} the Class 0 jet has significantly larger $\dot{M}_{\text{out}}(H_2)$ and $\dot{P}_{\text{out}}(H_2)$, suggesting that the difference is due to the earlier evolutionary stage. This is in line with the results of Bontemps et al. (1996) who found a stronger CO outflow momentum from Class 0s than from Class Is and attributed it to a decrease in the mass accretion rate with increasing age of the star. Studies of a larger sample of 23 Class 0 and Class Is by Caratti o Garatti et al. (2006), on the other hand, found no clear distinction between the two YSO classes when examining outflow H_2 luminosity versus L_{bol} . For comparison, we estimate the outflow H_2 luminosity from the dereddened flux in the $2.12 \mu\text{m}$ line, and get $L_{2.12}$ values of 0.025, 0.0016 and 0.0034 L_{\odot} for Flow 1, Flow 2 and Flow 3, respectively. The correction factor to apply to $L_{2.12}$ in order to get L_{H_2} is ~ 12 when assuming LTE and an average temperature of 2200 K (Caratti o Garatti et al. 2006) and give the values listed in Table 10.

As discussed in Sect. 3.6 our multi-epoch proper motions show that the velocities are time-variable. Thus, all discussions on mass flux here is based on the use of an average velocity over a 10 year time-span for each knot. Within the Class 0 flow there is a large variation in the estimated mass flow rates of the individual knots. Above all others, MHO 2234-A1+A2, which is the knot nearest to the Class 0 driving source (at a projected distance of ~ 1800 AU), stands out as particularly massive and fast-moving. This double-knot alone carries a mass flux of almost $1 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ and is the main contributor to the relatively high \dot{M}_{out} in this flow. It is probably the result of a recent burst of mass accretion, as these mechanisms are believed to be closely coupled.

Still, according to observed relations between the bolometric luminosity of Class 0/Class I sources and their mass flow rate from CO measurements (Shepherd & Churchwell 1996), the expected \dot{M}_{out} for a 4 L_{\odot} Class 0 source should be around $10^{-5} M_{\odot} \text{ yr}^{-1}$. This discrepancy is probably explained by the fact that our estimates concern only that part of the gas that is involved in the H_2 line emission, that is the warm molecular gas component. From these H_2 data alone, we have no information about the presence and contribution to the mass-flow rate of a colder molecular gas component or an atomic gas component. Although our deep imaging finds no emission from the knots in the H-band where strong [FeII] lines are located, this could be due to high extinction. As shown by Nisini et al. (2005) and Davis et al. (2011) \dot{M}_{out} of the molecular gas component can be 10 to 1000 times lower than \dot{M}_{out} from the atomic component.

The ratio of mass outflow to mass accretion, $\dot{M}_{\text{out}}/\dot{M}_{\text{acc}}$, is typically found to be of the order of 1/10 for Classical T Tauri stars, while there is a large scatter in the measured ra-

tios for younger YSOs, from 0.01 to 0.9 depending on tracers used (Antoniucci et al. 2008), while Caratti o Garatti et al. (2012) find an average ratio of 0.01 for Class I and very young YSOs when using $\dot{M}_{\text{out}}(H_2)$. If we can assume that the same holds here, we are witnessing a burst of mass accretion about 70 years ago with a mass accretion rate $\dot{M}_{\text{acc}} \sim 10^{-4} M_{\odot} \text{ yr}^{-1}$.

If the velocities were constant, the \dot{M}_{out} found for a knot would provide a measure of the instantaneous mass flow rate at a given time in the past, and hence give an idea about the accretion history. Although we know from the multi-epoch proper motions that the velocities of many H_2 emitting knots may vary with time, we take as a first approximation the average velocities (over 10 years) at face value, as done also when discussing dynamical age. We note the tendency for the space velocities to decrease with distance from the driving source, in particular for the southern arm of the Class 0 jet (Flow 1). Whether this is due to a slowing down of the jets, which could be expected as these shocks travel in a dense medium and may interact with the surrounding gas (entrainment), or it reflects a real variation in ejection speed, remains unclear. Also, as mentioned above, it is not clear what percentage of the total mass flux is traced by the shocked molecular hydrogen.

The three protostellar flows studied here are located in the same star forming core, hence, at the same distance from us, presumably in very similar physical conditions, and in addition the three driving sources are of similar bolometric luminosities. The knots in the Class 0 jet are both faster and more massive than the knots in the two Class I jets, suggesting a clear difference between the two evolutionary stages and supporting the idea that accretion and ejection is stronger during the Class 0 stage, as suggested by Bontemps et al. (1996). Nevertheless, in view of the emerging picture of the episodic nature of the accretion/ejection phenomenon, which is also supported by our time-variable velocities, we can not exclude that the observed difference between the Class 0 and the two Class Is presented here is also time-variable. Thus, it could be that we by chance study these sources at a moment dominated by the effects of a recent massive accretion burst in the Class 0 source.

5. Summary and Conclusions

1. We measured proper motions for 31 (out of 57 detected) knots in protostellar jets in the Serpens NH3 region (aka Serpens cluster B), using multi-epoch near-IR H_2 line imaging ($2.1218 \mu\text{m}$) with the same telescope/instrument setup over the period 2003 to 2013.
2. We find tangential velocities over the time-scales: 10 years, 8 years, 6 years, 4 years and 2 years for most of these knots. The 10 year base-line proper motions give typical velocities around 50 km/s and a maximum velocity of 190 km/s. While these can be viewed as the average velocities over 10 years, the shorter base-lines show evidence of time-variable velocities.
3. The knot fluxes over the 4 measured epochs are relatively stable and flux variability is detected for 45% of the knots, but only a few vary by as much as 30% or more in their flux. We find no correlation between flux variability and velocity variability, nor between flux variability and speed.
4. There was a burst in brightness around MHO 2235-A1 in 2011 as compared to 2009 with a disappearance again in 2013, a clear piece of evidence of the episodic nature of the jets.
5. Radial velocities were obtained for the knots for which we have K-band spectra, using all the available and sufficiently

- strong H₂ lines (typically 4-5 lines), yielding the space velocities.
6. Based on the knot velocities, the morphology, and published data on protostars in the region, we interpret our data to show at least three different jet flows in the field we monitored, of which two are bipolar. The three driving sources are suggested to be: MMS3 (Ser-emb-1), a low luminosity Class 0 source, Ser-emb-11, a binary Class I, and Ser-emb-17, another Class I source, all deeply embedded and previously studied from mid-IR to longer wavelengths.
 7. The dynamical ages of different parts of these flows are estimated, based on their separations from the driving source and their current velocities. These deduced ages are all < 5000 yrs, the youngest features < 100 yrs.
 8. Time-variable velocities are found in the ejecta from a Class 0 source, for the first time. We also find that the Class 0 jet has larger measured velocities than the two Class I jets.
 9. From the K-band spectra obtained for a subset of the brighter knots, we estimate the excitation temperatures, the average value being $T_{\text{ex}} = 2200 \pm 350$ K, which is typical for rovibrational states of H₂ in post-shock layers. Towards these knots we have also made a rough estimate of the extinction using the H₂ lines, and found values as high as $A_V = 58$ magnitudes. Column densities of H₂ were obtained from the dereddened line intensities. For 24 knots without spectra we estimated column densities through the $v=1-0$ S(1) line intensity.
 10. Column densities are combined with space velocities and knot location to derive the mass loss rates in the knots. We find that \dot{M}_{out} for the Class 0 jet is about two orders of magnitude larger than \dot{M}_{out} for the two Class I jets while the L_{bol} of the driving sources are all practically the same.

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