Physical and kinematical properties of a newly discovered star cluster and its associated jet in the Vela Molecular Clouds^{★,★★,★★★}

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Abstract. The star forming region associated with IRAS 08211-4158 and located in the Vela Molecular Ridge (VMR) has been investigated with low ($\mathcal{R} \approx 600$) and high resolution ($\mathcal{R} \approx 9000$) near infrared spectroscopy (1–2.5 μm) together with narrow band ([Fe II] and H₂) and broad band (*H*, *K*, *L*, *M*) imaging. The photometric results allow us to identify for the first time a young cluster with the less evolved star lying toward its center. Our results confirm that the most massive stars found in the clusters of the VMR do not form before the low mass ones. In particular, the only bipolar jet detected across the investigated field is driven by the most massive object which lacks an optical counterpart. Such a jet is composed of individual knots showing several H₂ and [Fe II] emission lines indicative of a coexistence of different shocks responsible for their excitation. Physical parameters of the emitting gas such as electron density, extinction and temperature have been derived from the low resolution spectroscopy. Some knots are already thermalized, while other present a stratification of temperature up to values of 5000 K. Through high resolution spectroscopy the [Fe II] lines profile for the majority of the knots can be resolved in a double peaked structure which is consistent with bow shock model predictions. Moreover, the radial velocity component is determined for different knots. Finally, by comparing [Fe II] images taken in different epochs, we have been able to derive the proper motion for some knots, hence to evaluate their total velocity ($\sim 300 \text{ km s}^{-1}$), the dynamical age and the jet inclination with respect to the plane of the sky.

Key words. stars: circumstellar matter – ISM: jets and outflows – ISM: kinematics and dynamics –
ISM: individual objects: Vela molecular clouds – ISM: individual objects: IRAS 08211-4158 –
ISM: individual objects: HH219 – infrared: ISM: lines

1. Introduction

The majority of the bipolar jets ejected by young stellar objects (YSOs), have been discovered by means of narrow band imaging in the optical band (i.e. with H α and [S II] filters). Sometimes, such jets present to the observer only their blue-shifted component, that on the near side of the molecular cloud. By imaging these jets in the near infrared (IR) through

the H₂ narrow band filter centered on the shock excited ro-vibrational line at 2.122 μm (1–0S(1)), the red-shifted component receding into the cloud becomes often observable if the extinction is not prohibitive ($A_V \lesssim 50 \text{ mag}$). This is the case of IRAS 08211-4158, an IR source without any optical counterpart, whose red-shifted jet component was only recently discovered through H₂ and [Fe II] imaging (Lorenzetti et al. 2002, hereafter L02). The blue-shifted jet associated to this YSO is labeled HH219 in the Reipurth’s General Catalogue of Herbig Haro objects¹ (HH) and was first identified by Graham (1991, hereafter G91). He studied, by means of optical spectroscopy, the radial velocity components of the HH with respect to the exciting source, identified as the infrared source No. 1 of the catalogue published by Persson & Campbell (1988). The same conclusion was reached as a result of an accurate study of the illumination of the nebulosities around IRAS 08211-4158

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* Based on observations collected at the European Southern Observatory, Paranal and La Silla, Chile (65.I-0150, 66.C-0158, 68.C-0020).

** 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/422/141>

*** Tables 3–6 are only available in electronic form at <http://www.edpsciences.org>

¹ <http://casa.colorado.edu/hhcat>

carried out by means of polarization maps by Scarrott et al. (1992). CO(1–0) data have been obtained by Wouterloot & Brand (1989): the IRAS source has the entry number 1134 in their catalogue and its spectrum presents high velocity wings indicative of the presence of outflowing gas. In the framework of our multifrequency study of the star formation in the VMR, the Persson & Campbell source No. 1 is listed as IRS 8–2 (Liseau et al. 1992; hereafter Paper I) according to our internal catalogue: it is classified as an intermediate luminosity Class I YSO at a distance of about 400 pc. We have also obtained narrowband imaging at $1.644 \mu\text{m}$ [Fe II] $a^4F_{9/2} - a^4D_{7/2}$ transition (L02): the spatial distribution of the [Fe II]/H₂ intensity ratio suggested the presence of a bow shock characterized by a dissociative component along the jet axis and a molecular component on the bow wings.

YSOs of intermediate mass (i.e. showing a luminosity of about $10^2 - 10^3 L_{\odot}$) tend to form in clusters rather than in isolation, as confirmed by several observational studies (e.g. Massi et al. 1999, 2000, 2003 – Papers III, IV, V, respectively, and references therein). This issue is of some relevance for the study of the jet properties of individual sources, since young IR clusters offer a unique chance to estimate the statistical occurrence of the jet phenomenon based on a coeval sample of YSOs.

Therefore we have firstly obtained, through near IR (H , K , L and M) broad band imaging, a census of the young stellar population around IRAS 08211-4158 to which algorithms for clustering analysis have been applied. Then, to have a better insight into the structure of the region, we have analysed high resolution ($R \approx 9000$) IR spectroscopy and narrowband imaging (centered at $1.644 \mu\text{m}$ and at $2.122 \mu\text{m}$) of the bipolar outflow, obtained with the ISAAC IR camera at the ESO-VLT, complemented with near IR low resolution ($R \approx 600$) spectroscopy (from 0.95 to $2.5 \mu\text{m}$) along the jet, obtained with the SofI IR camera at the ESO-NTT. These data, together with a new analysis of previously published (L02) narrowband ([Fe II]) and broadband images (H , K), allowed us to investigate the kinematical and physical properties of the protostellar jet and its parent cloud.

The structure of the paper is the following: in Sect. 2 we present our observations; in Sect. 3 we discuss the results of both imaging and spectroscopy and in Sect. 4 we derive the clustering properties along with the physical, kinematical and dynamical parameters of the region. Finally, our conclusions are summarized in Sect. 5.

2. Observations and data reduction

2.1. Imaging

The observations presented in this paper were obtained during three different runs (2001–2002) as summarized in Table 1.

Near IR images were obtained at the ESO-VLT with the ISAAC IR camera (Cuby et al. 2003), in the short wavelength (SW) mode ($0.148''/\text{pixel}$ scale and $2.5' \times 2.5'$ FoV) with the [Fe II] ($\lambda = 1.64 \mu\text{m}$; $\Delta\lambda = 0.025 \mu\text{m}$) and the H₂ ($\lambda = 2.13 \mu\text{m}$; $\Delta\lambda = 0.028 \mu\text{m}$) narrow band filters and in the long wavelength (LW) mode ($0.071''/\text{pixel}$ and $1.2' \times 1.2'$ FoV) for the L and M bands.

Dithering and nodding techniques were applied to all the observations. In addition, for the L and M bands, chopping was also employed in order to reduce the background contributions due to the fast sky variability.

All the raw data were reduced by using the IRAF² package, applying standard procedures for sky subtraction, dome flat-fielding and bad pixel removal.

Calibration was obtained by means of the photometric standard star HD 75223 (Bouchet et al. 1991). The zero-magnitude fluxes for the narrow band photometry have been calculated using a normalized black-body curve at $T = 11\,200 \text{ K}$ [$F(\lambda = 5550 \text{ Å}) = 3.44 \times 10^{-5} \text{ erg s}^{-1} \text{ cm}^{-2} \mu\text{m}^{-1}$]. The resulting fluxes are: $F_{\odot}(1.644 \mu\text{m}) = 1.16 \times 10^{-6} \text{ erg s}^{-1} \text{ cm}^{-2} \mu\text{m}^{-1}$ and $F_{\odot}(2.122 \mu\text{m}) = 0.463 \times 10^{-6} \text{ erg s}^{-1} \text{ cm}^{-2} \mu\text{m}^{-1}$.

In order to have a survey of the young stellar population of the field, to recognize the possible presence of a young cluster and to measure the proper motion of the observed knots, here we also consider our previously published narrow ([Fe II]) and broad band (H and K) images (L02), collected between 1996–1998 at the ESO 2.2-m telescope with the IRAC2b IR camera (FoV: $2' \times 2'$; scale: $0.49''/\text{pixel}$).

Aperture photometry was performed on the H , K , L , M images using the task *phot* in IRAF, after a search with *daofind* and a visual check of each frame. We chose a radius of ~ 1 full width half maximum (FWHM) and an annulus at ~ 2 FWHM ($\sim 1-2$ FWHM wide) in order to account for the highly variable background emission. An aperture correction was estimated on a few isolated stars using the task *mkapfile* in IRAF with a formal error of $0.02-0.03$ mag. We derived limiting magnitudes of $H \sim 18.2$, $K \sim 17.3$, $L \sim 15.2$ and $M \sim 12.5$. The measurements in the different bands have been merged together using the tasks *geomap* and *geoxytran* in IRAF to check the source matching. The equatorial coordinates of the sources were derived from the K frame as explained in Paper III and are hence calibrated on the HST Guide Star Catalogue (GSC). The photometry results are listed in Table 2³.

2.2. Spectroscopy

Low resolution spectroscopy was acquired during two different runs at ESO-NTT with the SofI near IR camera ($0.29''/\text{pixel}$ scale) (Lidman et al. 2000). As reported in Table 1, long slit spectra with different position angles (PA) were achieved for the blue (one slit) and the red lobe (two slits), in order to study the brightest H₂ emission regions of the outflow. The slit width was $1''$, corresponding to a spectral resolution of $\lambda/\Delta\lambda \approx 600$. To perform our spectroscopic measurements, we adopted the usual ABB'A' configuration, for a total integration time of 1200 s per slit. Each observation was flat fielded, sky subtracted and corrected for the curvature derived by longslit spectroscopy, while atmospheric features were removed by dividing the spectra by a telluric standard star (O8 spectral type),

² IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by AURA, Inc., cooperative agreement with the National Science Foundation.

³ Table 2 is only available in electronic form at CDS.

Table 1. Journal of observations. Imaging and spectroscopy.

Telescope/ Instrument	Date of obs. (y, m, d)	Band ($t_{\text{int}}(\text{s})$)				Target	
ESO-VLT / ISAAC	2001 Feb. 05	[Fe II] 1.644 (240), H ₂ 2.122 (240)				IRAS 08211-4158	
	2001 Feb. 06	L (600), M (600)				IRAS 08211-4158	
Telescope/ Instrument	Date of obs. (y, m, d)	Wavelength (μm)	t_{int} (s)	PA ($^\circ$)	Slit width ($''$)	$\mathcal{R}$	Encompassed region
ESO-NTT / SofI	2001 Jan. 12	0.95–2.50	1200	3	1	600	Blue lobe
	2001 Jan. 13	1.55–2.50	1200	110			Red lobe
	2002 Jan. 05	0.95–2.50	1200	341			Red lobe
ESO-VLT / ISAAC	2001 Feb. 05	[Fe II] 1.644	600	0	0.3	10 000	Blue lobe
				145.5			Blue lobe
				153.2			Red lobe
		H ₂ 2.122	600	0	0.3	8900	Blue lobe
				145.5			Blue lobe
				151.2			Red lobe
		Bry	600	128		0.3	IRS 8–2

normalized to the blackbody function at the star's temperature and corrected for hydrogen recombination absorption features intrinsic to the star. The wavelength calibration was retrieved from Xenon-Argon lamp lines. The flux calibration was obtained from the observation of three different photometric standard stars from the Carter & Meadow (1995) catalogue. Overlapping between the blue and red grisms has been made by using the [Fe II] 1.644 μm line, present in both the segments.

High resolution spectra around the [Fe II] ($\lambda_{\text{vac}} = 1.64399 \mu\text{m}$; Johansson 1978), 1–OS(1) H₂ ($\lambda_{\text{vac}} = 2.12183 \mu\text{m}$; Bragg et al. 1978) and Bry ($\lambda_{\text{vac}} = 2.16612 \mu\text{m}$; Erickson 1977) were obtained with the ISAAC IR camera, with a 0.3'' slit, corresponding to a nominal resolving power of 10 000 between 1.42 and 1.83 μm and 8900 between 1.84 and 2.56 μm . The instrumental profile in the dispersion direction, measured from Gaussian fits to the sky OH emission lines, was 43.0 and 43.3 km s^{-1} around 1.64 and 2.12 μm , respectively. The line velocity spread (Δv) was measured by deconvolving the measured instrumental profile with the observed line profile.

Targets and PA of the four slits are reported in Table 1. The first slit (H₂ and [Fe II], PA = 0°) encompasses the peak of the HH219 H₂ region. The second slit (H₂ and [Fe II], PA = 145.5°) points along the excitation axis of HH219 (mainly traced by the iron emission), while a third slit is positioned on the red lobe, with a different PA (153.2° for [Fe II] and 151.2° for H₂), because the ionic and molecular regions do not overlap. Finally, with the fourth slit (PA = 240°), centered around the Bry emission, we observed the IRS 8–2 source.

In these high resolution spectra, we adopted the same acquisition and reduction technique described above, for a total integration time of 600 s for each position. The wavelength calibration was performed using atmospheric OH lines

(Rousselot et al. 2000) with an accuracy of 1–3 km s^{-1} . In bright H₂ and [Fe II] spectra, in addition to the 2.12 and 1.64 μm features, we also detected the 2–1S(2) and 2–1S(3) H₂ lines ($\lambda_{\text{vac}} = 2.15421$ and 2.07347 μm ; Bragg et al. 1978) and two [Fe II] lines, namely ($a^4\text{D}_{1/2}-a^4\text{F}_{5/2}$) and ($a^4\text{D}_{5/2}-a^4\text{F}_{7/2}$) ($\lambda_{\text{vac}} = 1.66422$ and 1.67733 μm ; Johansson 1978). These lines were used to improve the radial velocity estimate. Thus we obtain a H₂ radial velocity uncertainty between 4 to 7 km s^{-1} and a [Fe II] uncertainty between 6 to 7 km s^{-1} . Finally, the flux calibration has been obtained using the standard star HD 75211.

3. Results

3.1. Broad band imaging

Figure 1 shows the Spectral Energy Distributions (SED's) and the contour plots of the K fluxes around the infrared source IRS 8–2 found by single channel photometry in Paper I. This coincides with source # 16 of Table 2.

Source # 16 is fainter by ~ 0.9 , ~ 0.4 , ~ 0.2 and ~ 0.2 mag in H , K , L and M , respectively, compared with the values given in Paper I. This is probably due to the size of the aperture used with the single channel photometer, which detected the diffuse emission around # 16, prominent in the H and K bands. There are few doubts that # 16 is the NIR counterpart of the IRAS source: it lies within the uncertainty ellipse (see Fig. 5 of L02) and is by far the brightest object at L and M . It also coincides (within $\sim 10''$) with the MSX source 5C_G259.7568–0.28370. This confirms the results from Paper III, i.e., that the emission from a single source appears to dominate at longer wavelengths ($> 2.2 \mu\text{m}$) with respect to all other objects in the fields of the IRAS sources selected in Papers I and II

Fig. 1. a) Spectral Energy Distributions of the NIR sources near # 16 (i.e. IRS 8–2) and **b)** contour plot of the K flux around the same source. The IRAS flux densities (solid line) and those for the MSX source 5C_G259.7568–0.28370 (asterisks) are also drawn in **a)**. The contours in **b)** are in step of $\sim 2\sigma$ and the sources are labeled according to Table 2. Right Ascension and Declination are arcsec offsets from the location of source # 16.

(Lorenzetti et al. 1993), even though these are often associated with clusters.

3.2. Narrow band imaging

In Fig. 2 we show the IRS 8 region as it appears in the H_2 1–0S(1) emission line (not continuum subtracted). The region is dominated by a large reflection nebula that hides the IRAS 08211-4158 source (a small box shows its position). Two bright outflows are located in the south east (namely HH219) and in the north west region along the same position angle (PA $\approx 153^\circ$), but symmetrically disposed with respect to the central source. A contour plot of the [Fe II] (1.644 μ m) emission line is superposed on the image. It is worth noting that the [Fe II] emission, more than the H_2 one, is well aligned with the IRS 8–2 source, tracing the jet axis, as already pointed out

Fig. 2. IRS 8 region: H_2 (2.122 μ m) image (not continuum subtracted) with superimposed contour plots of the [Fe II] (1.644 μ m) emission. The contours are 2, 4, 6 and $8\times$ the standard deviation to the mean background (1.5×10^{-16} erg s⁻¹ cm⁻² arcsec⁻²). The small central box shows the position of IRS 8–2 (RA = 08^h22^m52.2^s, Dec = -42°07'55.1'' (J2000.0)), the exciting YSO associated with IRAS 08211-4158. The slit positions are indicated by solid lines and labeled from 1 to 7. The adopted PA are: 0° (slit 1), 145.5° (slit 2), 152.2° (slit 3), 128° (slit 4), 3° (slit 5), 110° (slit 6), 341° (slit 7).

in L02. In that paper, we presented imaging and photometry of thirteen knots, seven in the blue lobe (labeled from B1 to B7) and six in the red one (labeled from R1 to R6). The identified knots correspond to peaks either of H_2 or [Fe II] emission.

Due to the higher spatial resolution, through VLT images it has been possible to better disentangle the morphology of these regions, allowing us to separate almost completely the highly excited shocked regions (traced by the [Fe II] emission) from the low excited gas (H_2), even along the jet axis.

Figures 3 and 4 depict the blue (SE) and red lobes (NW) in the [Fe II] and H_2 bands (left and right panels).

In these images we detect eleven more knots, five in the blue (B8–12), three in the red lobe (R7, R8 and R9) and three in

the central part of the nebula (*B0*, *R0* and *B13*). With reference to these newly identified knots, in Table 3 we show their sizes, the [Fe II] and H₂ fluxes and the coordinates. We do not find any significant variation in the fluxes of the previously discovered knots.

Blue and red lobes appear completely different in the [Fe II] and H₂ bands, showing a quite complex structure. In the [Fe II] imaging, HH219 (Fig. 3) is composed mainly of four bright knots (*B10*, *B3*, *B5*, and *B8*), roughly disposed along the jet axis, a structure reminiscent of subsequent shock events. A further [Fe II] emission region, located off-axis, is visible in the NE direction, coincident with the brightest H₂ knot *B6*. The H₂ morphology appears more complicated. Roughly, along the jet axis, a spatial anticorrelation between the molecular and the ionic emission emerges, since the majority of the H₂ emission is located outside that region.

Besides the bright *B6*, that, together with *B2*, *B4* and *B12*, could be the wing of an asymmetric bow shock, we detect two fainter arc-shaped regions. They lie orthogonal with respect to the jet axis and stand upstream (*B1*, *B11* and *B10*) and downstream (*B9* and *B7*) the shocked [Fe II] regions.

Also the red lobe [Fe II] emission (Fig. 4, left panel) appears composed primarily of four knots (*R7*, *R3*, *R6* and *R8*), roughly disposed along the jet axis. The strongest shock is represented by *R3*, with *R6* showing a bow shock shape. On the SW direction, an elongated H₂ emission region extends parallel with the jet axis, composed of knots *R1*, *R2*, *R4* (see Fig. 4, right panel). Along the axis three bright knots are detected (namely *R5*, *R6* and *R8*), these last emitting both in H₂ and [Fe II]. A further knot (labeled *R9*) lies off-axis behind *R8* and apparently does not seem to be correlated with the main flow.

Inside the nebula, through [Fe II] (1.644 μm) imaging (Fig. 5), there is evidence of a further jet coming out from IRS 8-2 with a PA $\approx 153^\circ$ (well visible along the SE direction). Following our classification, we labeled *B13* the brightest end of the SE jet. It lies about 6.1'' (i.e. ≈ 2500 AU) far from IRS 8-2. Further from *B13*, we find two more knots (named *B0* and *R0*) lying along the jet axis as well, symmetrically disposed with respect to the source, both emitting H₂ and [Fe II]. The presence of these inner knots points out that the activity of the outflow is still ongoing.

3.3. Low resolution spectroscopy

We obtained low resolution spectroscopy of eight knots (*B2*, *B3*, *B6*, *R1*, *R2*, *R6*, *R7*, *R9*). Out of these, *B3* and *B6* present spectra rich in both molecular and ionic lines, similar to other high excited HH objects (Nisini et al. 2002, hereafter N02). Figure 6 shows the spectrum of the *B6* knot, where the most prominent features are the [Fe II] and H₂ lines, combined with a few other ionic lines. The detected [Fe II] lines involve transitions between the first 13 fine structure levels (i.e. the levels connecting the terms $a^6\text{D}$, $a^4\text{F}$ and $a^4\text{D}$). The faintest lines (e.g. 1.600 and 1.664 μm) are visible only along the jet axis, as confirmed by our high resolution spectroscopy (see below). H₂ emission lines, involving vibrational bands from $v = 1$

up to $v = 4$, are detected in both *B3* and *B6* knots, indicating a high excitation of the gas. The strongest among the detected ionic features is the [C I] doublet at 0.983 and 0.985 μm , while at a lower S/N (~ 3) we also observe the two [S II] doublets at 1.029 and 1.032 μm and the He I (1.083 μm), that is blended with H₂ 2-0S(5) line in *B3*. Hydrogen recombination lines from the Paschen series (β and γ) are also detected in both knots.

The spectra of the other observed knots show H₂ and [Fe II] components, but other ionic features are weak or absent. In these knots we identify H₂ emission lines up to $v \leq 3$, indicating a lower excitation of the gas or a higher extinction.

In Tables 4–6 we list the fluxes (uncorrected for the extinction) of the identified lines together with their vacuum wavelength. Line fluxes have been obtained by fitting the profile with a single or double Gaussian in case of blending. The uncertainties associated to these data derive only from the rms of the local baseline multiplied by the linewidths (always comparable with the instrumental profile width). Lines showing fluxes with a S/N ratio between 2 and 3, as well as those blended, have been labeled. Additional uncertainties in the fluxes derive from both the absolute calibration ($\approx 10\%$), while another 10% has to be ascribed to the grism overlapping procedure.

Considering both the combined effects of the knot morphologies and the slit positions, there is agreement, inside the error uncertainty, between the photometric and the spectroscopic fluxes, with the exception of *B3* and *B6* whose 1-0S(1) line fluxes are spectroscopically brighter, because their spectra partially include emissions from knots *B4* and *B12*, respectively.

3.4. High resolution spectroscopy

In Table 7 we report [Fe II] and H₂ radial and *FWHM* velocities derived in each knot from the high resolution spectra. For those knots encompassed by more than one slit only the highest velocities are listed. The radial velocities are relative to the ambient molecular cloud, for which a velocity of 10.8 km s⁻¹ with respect to the local standard of rest (LSR) has been assumed (Paper I).

Position-velocity (PV) diagrams of the 1.644 [Fe II] line are presented in Figs. 7, 8 (blue lobe) and 9 (red lobe).

The PV diagrams relative to slit 1 and 2 (Figs. 7, 8) allow us to define the velocity variations along the jet axis (slit 2) and in the oblique direction (slit 1) chosen for encompassing knot *B6*. Along the jet axis we note the presence of two different velocity components in three (out of four) different knots (*B3*, *B4* and *B8*). The low velocity components (LVC) range between -27 and -57 km s⁻¹, with a trend for the radial velocity to increase moving towards the jet apex, while the higher velocity components (HVC) have v_r of the order of 100 km s⁻¹. We note that while the line widths in the LVC and HVC of *B3* and *B4* are similar (50–60 km s⁻¹), in *B8* Δv reaches a value comparable to the radial velocity (~ 110 km s⁻¹). For all the three knots the two components appear spatially coincident.

We can compare the results of our slit 2, with the optical (6200–6900 Å) spectra at $\mathcal{R} \approx 5600$, obtained by

Fig. 3. IRS 8 blue lobe (HH219): on the left and right panel, [Fe II] ($1.644 \mu\text{m}$) and H_2 ($2.122 \mu\text{m}$) (not continuum subtracted) images are shown, respectively. The labels indicate the position of the knots, including the new ones detected. The contour levels of the [Fe II] and H_2 images are 2, 4, 6 and $8\times$ and 2, 5, 10, 20 and $30\times$ the standard deviation to the mean background, i.e. $1.5 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ and $9 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$, respectively.

Fig. 4. IRS 8 red lobe: on the left and right panel, [Fe II] ($1.644 \mu\text{m}$) and H_2 ($2.122 \mu\text{m}$) (not continuum subtracted) images are shown, respectively. The labels indicate the position of the knots, including the new ones detected. The contour levels of the [Fe II] and H_2 images are 2, 4, 6 and $8\times$ and 2, 5, 10, 15 and $20\times$ the standard deviation to the mean background.

Table 7. [Fe II] and H₂ radial velocities and spread velocities of the individual knots of IRS 8 derived by high resolution spectroscopy, corrected for the cloud speed respect to the LSR ($v_{\text{LSR}} = 10.8 \text{ km s}^{-1}$ (Paper I)). When detected, low and high velocity components (LVC, HVC) are reported. Δv values are given whereas linewidths are resolved.

[Fe II]					H ₂		
knot	v_{rad} (km s ⁻¹)	Δv (km s ⁻¹)	v_{rad} (km s ⁻¹)	Δv (km s ⁻¹)	knot	v_{rad} (km s ⁻¹)	Δv (km s ⁻¹)
	LVC	LVC	HVC	HVC			
B3	-57	60	-90	50	B0	-1	...
B4	-38	68	-101	49	B2	-5	...
B5	-48	60	...	...	B3	-7	23
B6	-23	27	...	...	B4	-5	...
B8	-27	40	-115	111	B5	-4	10
R3	101	159	275	34	B6	-5	10
R4	72	140	...	...	B7	-12	20
R9	40	10	...	...	B8	-9	...
					B9	-2	10
					B10	-3	10
					B11	-3	...
					B12	-2	...
					B13	-1	11
					R5	5	21
					R6	3	33
					R8	6	23

Graham (G91) using roughly the same coordinates and PA adopted by us. He identified two different regions along the blue lobe (referred as cuts 3 and 4), roughly associated with our B8 plus B9 and B3 plus B4 and B5 knots, respectively. There is a good agreement between our mean (LVC + HVC) [Fe II] radial velocities in the two regions and the H α radial velocities found in G91, once corrected with respect to the LSR.

Moving in the oblique direction with respect to the jet axis (slit 1, Fig. 7), we note that the speed decreases (in modulus), moving from the axis (B3) (-57 km s^{-1}) to the edge (B6) (-23 km s^{-1}). Also the spread velocity (Δv) value drops going from B3 (60 km s^{-1}) to B6 (27 km s^{-1}). With this slit orientation, we observe only components at low velocities. Hence we see narrow single peaked profiles on the edges of the shock and double peaked lines along the central axis, as predicted in bow shock geometrical models (see e.g., Davis et al. 2001).

In the red lobe (slit 3, Fig. 9), we also observe that the maximum radial velocity and line width are detected at the apex of the jet (knot R3), which however shows velocity values significantly higher than in the blue lobe ($v_r = 101 \text{ km s}^{-1}$, $\Delta v = 159 \text{ km s}^{-1}$). There is also evidence of a fainter emission at even higher velocity ($\sim 270 \text{ km s}^{-1}$) in knot R3.

At variance with those of [Fe II], the H₂ velocities do not show significative variations along and the jet axis and in the oblique direction (Table 7): the radial velocities range between -1 and -10 km s^{-1} in the blue lobe, and 3 – 6 km s^{-1} in the red lobe. Linewidths were resolved from the instrumental

profile only for the brightest knots and are of the order of 10 – 20 km s^{-1} .

Finally, the spectrum corresponding to our slit 4 is centered around Bry line and refers to the IRS 8–2 source, revealing a broad blue-shifted Bry emission, roughly symmetrical in shape, at $-33(\pm 4) \text{ km s}^{-1}$ and with a spread velocity of about 150 km s^{-1} . Such emission appears spatially coincident with the source. A similar behaviour, i.e. blue-shifted Bry line with such a spread in velocity, has been found in several Class I YSO's (e.g. Najita et al. 1996; Davis et al. 2003) and has been interpreted as both emission coming from hot gas in the accretion flow or originating from a compact ionized wind close to the star (Nisini et al. 2004).

Finally, also for high resolution spectroscopy we have measured the H₂ and [Fe II] fluxes, in order to derive physical parameters for those knots not encompassed by our low resolution spectroscopy, as well. Such fluxes have been measured by integrating the intensity profile of each knot over all the velocity components. The analysis and discussion, together with low resolution data, are presented in Sects. 4.2 and 4.3.

4. Data analysis and discussion

4.1. The nature of the cluster's stellar population

In order to check whether IRS 8–2 is actually embedded in a star cluster, as a visual inspection of our frames does suggest, we employed the methods discussed in Paper IV. Hence, as a first step we constructed a contour plot of the surface stellar

Fig. 5. IRS 8 central region: [Fe II] ($1.644 \mu\text{m}$) image (not continuum subtracted) in logarithmic scale. The labels show the position of IRS 8–2 source and of the new knots discovered.

density by counting all K sources in $20''$ -wide square bins offset by $10''$ both in Right Ascension and in Declination. Next, we derived a radial surface density distribution $n(r)$ by counting all K sources in $6''$ -wide annuli centered on the location of IRS 8–2. We assumed the same completeness limit as in Papers IV and V ($K = 15.5$), which is consistent with the estimated limiting magnitude (i.e. more than 1.5 mag larger), and counted only sources below the completeness magnitude. Both the contour plot of the stellar surface density and the radial density distribution are shown in Fig. 10. Due to the field projected closeness to clouds C and D and the fact that IRS 8 is at about the same distance as those regions, we can expect that also the field stars' surface density is roughly the same as found towards clouds C and D. In Papers IV and V we estimated this to be roughly 1 star per unit cell (i.e. $\sim 10 \text{ stars arcmin}^{-2}$) when excluding objects fainter than $K = 15.5$. It is clear from Fig. 10 (see also Table 8) that the peak surface density largely exceeds the field mean value *plus* 3σ and that $n(r)$ increases towards IRS 8–2. Hence, this source lies in a star cluster. We derived the cluster properties, which are listed in Table 8, as explained in Paper IV. These are quite similar to those exhibited by the clusters studied in Papers IV and V.

The nature of the cluster's stellar population can be assessed using NIR magnitude-colour (MCD) and colour-colour (CCD) diagrams. Figure 11 shows $H - K$ vs. $K - L$, $K - L$ vs. $L - M$ and K vs. $H - K$. A large fraction of the sources imaged at L display a NIR excess in the CCD of Fig. 11a, indicating that the cluster is quite young. Adopting a distance of 400 pc, the zero age main sequence (ZAMS) from B0 to M5 stars is drawn in the MCD (Fig. 11c), based on colours from Koornneeff (1983) and absolute magnitudes from Allen (1976). Isochrones for 10^6 yr old pre-main sequence

(pms) stars (0.1 to $6 M_{\odot}$) are also drawn using the evolutionary tracks of Palla & Stahler (1999), after being reddened by $A_V = 0, 10, 20$ and 30 mag according to the extinction law of Rieke & Lebofsky (1985). It can be noted that IRS 8–2 is the brightest and reddest source in the MCD; most of the sources brighter than $K \sim 13.5$ exhibit a reddening in the range $A_V \sim 15$ – 30 mag (actually less, since an amount of colour excess is expected in such young stars). They can be also checked to lie spatially very close to IRS 8–2 (within $20''$ – $30''$). For $K > 13.5$, a concentration of stars with $A_V < 15$ mag is evident in the MCD; a fraction of them may be represented by background stars shining through the molecular gas.

If an age of 10^6 yr is assumed for the cluster, which would be consistent with the ages inferred for the clusters studied in Papers IV and V, then it can be easily checked in Fig. 11c that the completeness limit in K results in a *mass* completeness limit of $\sim 0.1 M_{\odot}$ at $A_V = 30$ mag. Most of the found sources lie below the reddening line of a $0.1 M_{\odot}$ star. Given the estimated number of members ($I_c^4 = 41$ in Table 8), this implies that a large fraction of them should have masses in the brown dwarf regime. However, the issue is sensitive both to the age and to the distance. The fraction of very low-mass stars and brown dwarfs would be much less if i) either all cluster stars or the less massive ones were actually older than 10^6 yr; ii) the distance was larger than estimated (e.g., IRS 8 could be at 700 pc, the same distance as clouds C and D). In particular, we find 11 sources below or at the mass limit of $0.1 M_{\odot}$ with also a measurement at L (most of the others simply lie outside the field of view of the L image); 5 of them exhibit a NIR excess in the $H - K$ vs. $K - L$ diagram of Fig. 11a and are then

⁴ I_c is the indicator of cluster richness, i.e. the number of sources corrected for foreground/background contamination.

Fig. 6. 0.95–2.5 μm low resolution spectrum of knot B6 in HH219. An asterisk near the line identification marks the detections between 2 and 3 sigma.

Fig. 7. Slit 1: [Fe II] 1.644 μm P-V diagram for HH219 (along the wing of the bow shock). *Left:* contour plot image with the slit superimposed; north and east are indicated. *Right:* radial velocities corrected for the cloud speed with respect to the LSR.

Fig. 8. Slit 2: [Fe II] 1.644 μ m P-V diagram for HH219 (along the jet axis). See caption Fig. 7 for details.

Fig. 9. Slit 3: [Fe II] 1.644 μ m P-V diagram for IRS 8 red lobe. See caption Fig. 7 for details.

very young stars and probable cluster members. If isochrones of 10^7 yr are used, all of them become consistent with $\geq 0.1 M_{\odot}$ pms stars, whereas the reddening sequence of a $6 M_{\odot}$ remains roughly at the same position as that for 10^6 yr old pms stars.

As can be seen in Fig. 10a, even though the field of view at L is smaller than that at K , the sources with a measured L appear to concentrate towards the cluster's center. A fraction of these clearly exhibit a NIR infrared excess in the CCD of

Table 8. Physical parameters of the star cluster associated with IRS 8.

Size (2R) (pc)	I_c	Peak surface density (pc $^{-2}$)	Volume density (pc $^{-3}$)
0.16	41 ± 3	7.4×10^3	3.8×10^4

Fig. 10. a) Contour plot of the stellar surface density and **b)** radial stellar surface density $n(r)$, in arcmin^{-2} , versus the projected distance r from IRS 8-2 (both derived from the K image). The contour plot was obtained by counting sources in square bins of $20'' \times 20''$, offset by $10''$. Right Ascension and Declination are arcsec offsets from the location of IRS 8-2. The lowest contour in **a)** amounts to 20 stars arcmin^{-2} , roughly 2 times the mean field star density, and the steps are 20 stars arcmin^{-2} , corresponding to intervals of $\sim 2\sigma$. The small dashed box in **a)** delineates the field of view of the L (and M) image; the filled squares are K sources with a measured L , the crosses are K sources without a measured L .

Fig. 11a, confirming their early evolutionary stage. The scatter in the CCD is partly due to the inclusion of faint sources and partly (possibly) due to source variability, since the HK and LM images have been taken a few years apart. One third of the sources with a measured L have been also detected at M , in particular all those labeled in Fig. 1b, excepted # 15. Hence, the most intense M sources concentrate towards the cluster's center, as well.

In total, there are 5 sources within $10''$ of IRS 8-2 with an infrared excess both at L and at K (# 12, IRS 8-2, 18, 19, 20). We had some concern in that all of these lie on the left of the reddening band of the main sequence in the $K-L$ vs. $L-M$ CCD. Actually, the colours of IRS 8-2 source are consistent with those measured through single channel photometry and listed in Paper I. It is also easy to check that a few of the sources studied in Papers III and V for which the single channel photometry at L and M (from Papers I and II) appears to be contributed by a single object (asterisks in Fig. 11b) fall on the left of the reddening band of the main sequence in the $K-L$ vs. $L-M$ CCD, as well. We also plotted the colours of young stellar objects in different star forming regions from the literature (crosses in Fig. 11b; Benson et al. 1984; Cohen & Schwartz 1983; Wilking et al. 1989; Leinert & Haas 1989), finding that still a few of them fall on the left of the reddening band.

During a survey aimed to detect the 1.3 mm continuum emission of the young VMR members (see Paper III), we have obtained for IRS 8-2 the value of 495 ± 14 mJy. Integrating the SED from $1.65 \mu\text{m}$ to 1.3 mm, we obtain for this source a bolometric luminosity value of $642 L_{\odot}$ ($624 L_{\odot}$ from $12 \mu\text{m}$ to 1.3 mm). This corresponds to an accreting protostar of $\sim 5 M_{\odot}$, according to Palla & Stahler (1993). If IRS 8 was located at the distance of clouds C and D, the bolometric luminosity would be $\sim 2 \times 10^3 L_{\odot}$ and the mass would be $\sim 6 M_{\odot}$. These luminosity values are also representative

of a $B2-B3$ ZAMS star (Panagia 1973), hence the mass does not depend much on age. The found I_c is consistent with the bolometric luminosity according to the relationship shown in Fig. 16 of Paper V.

Moreover, from the flux of the $\text{Br}\gamma$ observed towards the source, adopting $A_V = 40$ from colour-colour diagrams of Fig. 11, we can compute the number of ionizing photons needed to produce such emission, assuming that case B recombination applies. We found $\log N = 44.9$, which is consistent with the number of photons of the Lyman continuum expected from a $B2$ star (Thompson 1984).

We have shown that the jet driving source, IRS 8-2 or # 16 according to Table 2, is a very young star of $5-6 M_{\odot}$ embedded in a young cluster with an age of 10^6-10^7 yr. However, it can be noted in Fig. 11c that IRS 8-2 lies well above the reddening sequence of a 10^6 yr old pms star of $6 M_{\odot}$. If it was more distant than assumed, the isochrones would move downward in the MCD (whereas IRS 8-2 would become more luminous but only slightly more massive) enhancing the difference. Conversely, if it was less distant, the isochrones would move upward minimizing the difference but increasing too much the fraction of sub-stellar cluster members. Hence, an actual large infrared excess emission at K is evident for IRS 8-2, showing that the most massive star of the cluster is also the less evolved one. A small colour excess (and a very large extinction) is also apparent in Fig. 11a and a more consistent one in Fig. 11b. The large fraction of sources with an infrared excess found close to IRS 8-2 also suggests a sort of evolutionary segregation, with the less evolved stars in the clusters lying towards its center. This also implies a mass segregation, since all the brightest ones appear to concentrate towards the cluster's center. In particular, this confirms the results from Paper V, i.e., that the most massive stars found in the clusters of the VMR do not appear to form before the low mass ones.

Fig. 11. **a)** $H-K$ vs. $K-L$, **b)** $K-L$ vs. $L-M$ and **c)** K vs. $H-K$ diagrams for the sources found towards IRS 8. The position of IRS 8-2 is labeled in each frame. Filled squares mark sources with a measured M in **a)** and with a measured L in **c)**. Dashed lines in the colour-colour diagrams indicate the reddening of an A0 star according to Rieke & Lebofsky (1985) and crosses mark $A_V = 0, 10, 20, 30$ and 40 mag. The small solid line around (0,0) in **a)** and **b)** is the main sequence (from Koornneeff 1983). The labeled vertical line in **c)** is the zero age main sequence from M 5 to B0 stars (at a distance of 400 pc). The four displaced lines in **c)** are the isochrones for 10^6 yr old pre-main sequence stars at 400 pc with masses in the range $0.1-6 M_\odot$ (according to the evolutionary tracks of Palla & Stahler 1999) reddened by $A_V = 0, 10, 20$ and 30 mag. The long arrow indicates a reddening $A_V = 20$ mag. The small arrows are lower or upper limits. Crosses and asterisks in **b)** are young stellar objects from the literature and Papers I, II, respectively (see text).

Finally, observational evidence is given that the jet is associated with the most massive and less evolved object in the cluster. While recognizing IRS 8-2 as the youngest object in the field could quite naturally explain why we have not detected any other jet across the surveyed area, the consequence of having found an intermediate mass driving source (whose luminosity is about $600 L_\odot$) deserves to be examined in more detail. We notice that the extinction corrected H_2 luminosity⁵ of all the knots amounts to about $1 L_\odot$, implying an $L_{H_2}/L_{bol} \sim 2 \times 10^{-3}$. This is a value typically found in jets from Class I low mass sources (e.g., Stanke 2000), showing that the same concepts and properties derived for $\sim 1 L_\odot$ exciting sources can be applied to higher luminosity objects as well. The extension of such considerations to sources with higher masses needs to be further investigated. Indeed evidences for H_2 jets from O and early B spectral type sources are still sparse (e.g., Nanda Kumar et al. 2002). Fuller et al. (2001) detected an IR jet from a young B1 in Br α (but not in H_2), maybe indicating the prevalence of dissociated gas around massive objects.

4.2. [Fe II] lines analysis

[Fe II] and H_2 lines represent powerful diagnostic tools to study the physical properties of both the ionized and neutral outflow components.

The line fluxes of the observed objects have been firstly dereddened. The ratio of the two brightest [Fe II] transitions at 1.257 and $1.644 \mu\text{m}$ (i.e. $a^4D_{7/2}-a^6D_{9/2}$ and $a^4D_{7/2}-a^6F_{9/2}$), coming from the same upper level, has been used to derive the reddening E_{J-H} (e.g. Gredel 1994, N02) towards the observed objects and to compute the visual extinction (A_V) adopting the Rieke & Lebofsky (1985) extinction law and using the energies and radiative rates given by Nussbaumer & Storey (1988).

The individual values are reported in Table 9. As anticipated (L02), the red-shifted lobe has a higher extinction estimated between 9 and 12 mag in V band, while a value around 3 mag is found for the blue lobe.

In order to better understand the connection between the physical and kinematical properties of the studied region, it is noteworthy to derive the electron density (n_e) of the gas from both low and high resolution spectroscopy. As already explained in N02, we used three different [Fe II] dereddened line ratios (i.e. $1.644 \mu\text{m}/1.600 \mu\text{m}$, $1.644 \mu\text{m}/1.533 \mu\text{m}$ and $1.644 \mu\text{m}/1.677 \mu\text{m}$) to derive n_e . In fact these ratios are poorly sensitive to the gas temperature (the excitation energy of the different lines ranges from $\sim 11\,000$ to $\sim 12\,000$ K), but, because of the different line critical densities (between 10^4 and 10^5 cm^{-3}), they can be a good diagnostic tool for estimating n_e . For those knots observed only by means of high resolution spectroscopy, we used the only available ratio ($1.644 \mu\text{m}/1.677 \mu\text{m}$). Inside the error bar, we did not

⁵ H_2 luminosity is calculated through the relationship $L_{H_2}(\text{total}) = \alpha \times L_{H_2}(2.122 \mu\text{m})$. Assuming LTE conditions at 2000 K, the factor α is of the order of 10, but recent results (see e.g., Giannini et al. 2002) have demonstrated how the gas temperature in HH/jets can easily reach values up to 5000 K (see also Sect. 4.3) and, as a consequence, a much more appropriate estimate for α is about 15.

Table 9. Parameters of the individual knots of IRS 8 derived from [Fe II] and H₂ line analysis.

knot	$A_V([\text{Fe II}])^1$ (mag)	n_e (10^4 cm^{-3})	T (K)	$A_V(\text{H}_2)^2$ (mag)
<i>B2</i>	4 ± 4	...	2360 ± 380	3
<i>B3</i>	3.1 ± 0.2	0.2–0.8; 0.6–0.9*	3980 ± 330	3
<i>B4</i>	...	0.2–0.7*	$2620 \pm 160^*$	...
<i>B5</i>	...	0.3–0.9*	$2460 \pm 160^*$	...
<i>B6</i>	2.0 ± 0.4	0.2–0.8	3420 ± 200	3
<i>B8</i>	...	1–4*	$2440 \pm 210^*$	...
<i>R1</i>	9 ± 3	...	2820 ± 200	13
<i>R2</i>	11 ± 2	...	2430 ± 330	13
<i>R3</i>	...	1.6–5*	...	...
<i>R5</i>	...	...	$2655 \pm 300^*$	...
<i>R6</i>	...	>0.5	3220 ± 190	13
<i>R7</i>	11 ± 3	...	...	...
<i>R8</i>	...	...	$2440 \pm 210^*$	...
<i>R9</i>	12 ± 4	>0.3	2920 ± 380	13

Notes: ¹ derived from 1.644 and 1.257 μm [Fe II] line ratio.

² Errors are estimated around 1 mag for *B3* and *B6* and 3–5 mag for the remaining knots.

* Values computed through high resolution spectroscopy: T derived from 1–0S(1), 2–1S(3) and 2–1S(4) H₂ lines, and n_e from the ratio 1.644/1.678 [Fe II] lines.

note any difference between n_e values derived from the HV and LV components. The computed values are reported in Table 9. The n_e estimates derived from the low and high resolution spectroscopy are almost complementary and in agreement when both the determinations were possible (i.e. knot *B3*) (ISAAC values are labeled with an asterisk). In the blue and red lobe the higher values of n_e are found where radial velocities are greater (i.e. in *B8* ($1-4 \times 10^4 \text{ cm}^{-3}$) and *R3* ($1.6-5 \times 10^4 \text{ cm}^{-3}$) respectively). For the remaining red lobe knots, due to the low signal-to-noise of the involved lines, we give just a lower limit for n_e . In the blue lobe for *B6*, *B5*, *B4* and *B3* we find similar values ($0.2-0.9 \times 10^4 \text{ cm}^{-3}$).

Finally, it is possible to compare the average value of n_e found on the blue lobe axis with the results of G91. Through their observed [S II] doublet ratio (at 6716 and 6731 Å), we estimated an average electron density around $0.6 \times 10^3 \text{ cm}^{-3}$, that is an order of magnitude lower than the value computed in the near IR ($\sim 0.8 \times 10^4 \text{ cm}^{-3}$). This substantially confirms the already found evidence (see e.g., Oliva et al. 1990; N02) that the near IR [Fe II] emission traces the densest and most extinguished regions of the ionized gas with respect to the [S II] optical doublet.

4.3. H₂ lines analysis

As well known, the H₂ and [Fe II] emissions are unlikely to originate in the same region, even if, due to perspective effects, sometimes they appear spatially coincident (see e.g., Reipurth 2000; N02).

In this framework, the IRS 8 region represents a valuable case to study separately these two emission regions. It is therefore important to know whether the two emitting regions suffer from different local extinction or the observed reddening is mainly due to the parent cloud.

Different H₂ transitions, coming from the same upper level, can be used to give an independent determination of A_V to be compared with the value derived from the [Fe II] lines. If the extinction is not high ($A_V \leq 5$), some bright pairs (e.g. 2–0S(*i*)/2–0Q(*i*+2) and 3–1S(*i*)/3–1Q(*i*+2)) lying between 1 and 1.35 μm are better suited for this aim than the 1–0S(*i*)/1–0Q(*i*+2) transitions (see e.g. Giannini et al. 2004), the latter being heavily affected by poor atmospheric transmission.

We estimate an A_V of 3 ± 1 magnitudes for the blue lobe and 13 ± 3 magnitudes for the red lobe (see Table 9). A comparison with A_V values obtained with the [Fe II] lines shows that, within the errors, there is no difference in the results, meaning that the extinction is a large scale effect mainly originated in the medium interposed between the region and the observer.

Another important physical parameter that can be estimated from the H₂ line ratios is the temperature of the molecular gas. This is given by the slope of the rotational diagrams, where the column densities of the H₂ lines, divided by their statistical weights and corrected for the extinction, are plotted against their excitation energies (ranging from 5000 to $\sim 30\,000$ K in the near IR).

The rotational diagrams for the different knots observed are presented in Figs. 12 and 13. The lines coming from different vibrational levels are indicated with different symbols. In these

Fig. 12. Rotational diagrams of blue lobe knots *B2*, *B3* and *B6* derived from low resolution spectroscopy. Different symbols indicate lines coming from different vibrational levels, as coded in the upper right corner of each box. The straight lines represent the best fit through the $v = 1$, $v = 2$, 3, 4 (solid lines) and through all the data (dashed line). The derived temperatures are also indicated in the upper right corner of each box.

diagrams only the transitions with a $S/N > 3$ and not affected by blending with other lines are reported. The 1–0Q(i) transitions ($i = 1$ –6) are shown in the diagrams but not used in the analysis of some knots (*B2*, *B3*, *B6* and *R2*), since their fluxes are not reliable because of the poor atmospheric transmission at wavelength greater than $2.3 \mu\text{m}$.

From the diagrams shown in Figs. 12 and 13, relative to the blue and the red outflow lobes respectively, we note clear differences in the H_2 excitation of the various knots. *B3* and *B6* show transitions with v up to 4, tracing gas temperatures up to ~ 5000 K. Here thermal equilibrium is not reached by all the observed lines and different vibrational states are excited at different temperatures. As we have outlined in previous papers (e.g. Giannini et al. 2002, 2004, N02) this behaviour is common to other HH objects and it indicates a stratification of the gas temperature inside the considered emission knots. The lower vibrational levels (i.e. $v = 1, 2$) trace the cooler region of the gas (≤ 3000 K), while the higher the hotter. In the rotational diagrams we plot the average temperature (indicated with a dashed line) and the lower and higher temperature (solid lines) for the knots *B3* and *B6*. On the other hand, rotational diagrams for knots *B2*, *R1*, *R2*, *R6* and *R9* (in Figs. 12 and 13) are well fit by a single temperature, which should be an indication that they are already thermalized. For the knots in the red lobe, however, due to their higher extinction, we cannot exclude the possibility that we are not able to observe the gas components at higher temperatures. Such components are indeed traced through the emission of lines with high excitation energies ($E \geq 20\,000$ K), which are mainly located between 1 and $1.4 \mu\text{m}$ and thus more affected by the reddening.

For those knots observed only through high resolution spectroscopy, we were unable to construct proper rotational diagrams, and thus an estimate of their temperature has been obtained only from the ratios of the 1–0S(1), 2–1S(2) and 2–1S(3) lines (see Table 9). We derive temperatures ranging between 2400 – 2700 K, but since the considered lines trace only the low temperature component, we cannot infer whether higher excitation components are present or not in those knots.

4.4. Kinematical properties of IRS 8 outflow

4.4.1. Measuring proper motions from [Fe II] narrow band imaging

It is worth noting that the [Fe II] imaging can be a powerful tool to compute proper motion of jets lying near the plane of the sky and suffering extinction, thus not observable through optical ionic tracers. In addition, the iron lines, tracing jet components with velocities higher than those outlined by the H_2 molecular lines, allow us to detect the motion of the knots in shorter times.

Aiming to measure the proper motion ($''/\text{yr}$) of the knots we have analysed our [Fe II] ISAAC image in comparison with previously published imaging (L02), achieved three years before at ESO 2.2-m telescope with the IRAC2b IR camera. Although this latter provides less resolved images ($0.507''/\text{pixel}$) with respect to ISAAC, if one considers a tangential velocity $\geq 100 \text{ km s}^{-1}$ for the [Fe II] features, assuming a distance of 400 pc to the source, a relative motion $\geq 0.16''$ is expected in 3.1 years, that is, detectable in knots observed with a high enough S/N ratio.

Fig. 13. Rotational diagrams of red lobe knots *R1*, *R2*, *R6* and *R9* derived from low resolution spectroscopy. See caption Fig. 12 for details.

In order to analyse our two epoch images, we had to register them by applying linear geometric transformations (translation, rotation and rescaling), derived by matching the positions of many field stars (~ 60). The error introduced by the registration process is measured by the mean difference in the centroid positions of the stars of the two images. Due to local geometrical distortion, we found a different accuracy, depending on the zone of the image, resulting in an error of $0.10''$ and $0.15''$ for the blue and the red lobe regions, respectively. Then we derived the proper motion and the v_{tan} direction (θ) correlating each knot of the two images and obtaining the most probable shift between the two epochs. This produces a further error of $0.05''$ due to the quantization of the process. The total error derived by conservatively summing up both uncertainties is therefore estimated $0.15''$ and $0.2''$ for the blue and the red lobe respectively.

The tangential velocities were computed by assuming a distance of 400 pc and using the following relation (Chrysostomou et al. 2000):

$$v_{\text{tan}} = 1.587\pi p d \quad (1)$$

where V_{tan} is the tangential velocity projected on to the plane of the sky, p is the proper motion and d is the distance to the source in pc; the factor 1.587π derives from converting $''/\text{yr}$ to km s^{-1} .

Here we are assuming that the measured proper motions can be directly translated in tangential velocities, which means that knot proper motions trace actual fluid motions and not wave pattern speeds.

We were able to detect proper motions only for the bright knots *B3*, *B5*, *B8* obtaining values of 0.17, 0.11 and $0.15''/\text{yr}$ (between 2 and 4σ). These correspond to tangential velocities of $340 \pm 90 \text{ km s}^{-1}$, $220 \pm 90 \text{ km s}^{-1}$ and $290 \pm 100 \text{ km s}^{-1}$

respectively. For *R3* in the red lobe we can only estimate an upper limit of $\sim 380 \text{ km s}^{-1}$.

Besides the tangential velocities, proper motions large uncertainties affect also the computed v_{tan} direction of the knots. For HH219 we obtain an average value of $165^\circ \pm 40^\circ$. All the inferred kinematical and dynamical parameters are reported in Table 10.

4.4.2. Inclination, velocity and dynamical age

Combining both tangential and radial velocities, it was possible to compute the inclination angle (i) of the flow with respect to plane of the sky, deriving $i = 13^\circ \pm 4^\circ$, which means that the knots lie almost orthogonal with respect to the observer. This is in good agreement with the quite low radial velocities found for both the H_2 and $[\text{Fe II}]$ emissions and those derived from the optical spectroscopy in G91.

Once known the angle i , the total velocity can be derived by multiplying the radial or tangential components by $(\sin i)^{-1}$ and $(\cos i)^{-1}$, respectively. The total velocity reported in column four of Table 10 has been obtained from the $[\text{Fe II}]$ radial component with values between 100 and 400 km s^{-1} . Using values of Table 7 for the H_2 component, a velocity ranging between 5 to 50 km s^{-1} is derived, that is below or near the limit for H_2 dissociation in classical shock models.

An important parameter to derive the age of the jets components, is represented by the dynamical age (τ_{dyn}), that is, the ratio between the distance of the emission knot from the YSO (corrected for the inclination angle i) and its total velocity. The obtained values have been calculated using the $[\text{Fe II}]$ component. For those knots that show two velocity components, τ_{dyn} has been derived by averaging the two values, except for *R3*,

Table 10. Dynamical and kinematical parameters of the individual knots of IRS 8 derived by imaging and high resolution spectroscopy. Velocities have been corrected for the cloud speed with respect to the LSR ($v_{\text{LSR}} = 10.8 \text{ km s}^{-1}$ (Paper I)). Dynamical ages (τ_{dyn}) have been calculated assuming a distance of 400 pc to the source using the [Fe II] component. Total velocity has been derived mainly from radial velocity corrected for the inclination ($i = 13^\circ \pm 4^\circ$) of the object with respect to the plane of the sky.

knot	v_{rad} (km s^{-1})	v_{tan} (km s^{-1})	θ^* ($^\circ$)	v_{tot} (km s^{-1})	Proper motion ($''/\text{yr}$)	τ_{dyn} (yr)
B3	-73 ± 7^a	340 ± 90	165 ± 60	320 ± 100	0.17 ± 0.05	360 ± 110
B4	-70 ± 7^a	...	...	310 ± 100	...	350 ± 110
B5	-48 ± 7	220 ± 100	165 ± 70	210 ± 80	0.11 ± 0.05	510 ± 190
B8	-71 ± 7^a	290 ± 100	165 ± 60	320 ± 100	0.15 ± 0.05	290 ± 90
R3	101 ± 6^b	≤ 380	...	440 ± 130	≤ 0.2	160 ± 50
R4	72 ± 7	...	...	320 ± 100	...	210 ± 60
R9	40 ± 7	...	...	180 ± 70	...	220 ± 90

Notes: * The v_{tan} direction.

^a A mean value between LVC and HVC has been assumed.

^b Only LVC component used.

Fig. 14. [Fe II] $1.644 \mu\text{m}$ normalized line profile of knot B3.

where only the LVC has been considered, representing the bulk of the knot. In this way we compute a dynamical age between 300 and 500 years for the blue lobe and of ~ 200 years for the observed knots in the red lobe. The results are summarized in column seven of Table 10. The marginal difference between the dynamical ages of the two lobes could be originated by the assumption of a constant velocity. In this sense, these values have to be considered as a rough estimate of the flow age.

These timescales of only few hundreds years are typical of small scale HH jet (see e.g., Davis et al. 2000; McGroarty et al. 2003). Indeed the farthest knots we observe in the outflow (i.e. B10 and R7) are located, respectively, about 0.12 and 0.08 pc far from the progenitor, with dynamical ages lower than 10^3 years. The presence of more distant knots can be ruled out by inspecting an H_2 large field mosaic realized with the SofI IR camera (F. Strafella, private communication), where no further emission regions in a $4'$ radius around IRS 8-2 (i.e. roughly 0.48 pc distant from the source) are detected.

4.4.3. Double peaked velocities: Comparison with bow shock models and observations

The observation of two spatially coincident velocity components in the [Fe II] PV diagrams deserves some discussion about their origin. Up to now, the [Fe II] HV and LV components have been clearly observed only in W51H₂J192339.7+143131 (Hodapp & Davis 2002), an outflow in the massive star forming region W51. It is remarkable the fact that, with the exception of knot A, their observations, like ours, do not show a splitting of the H_2 lines, but only a slightly broadening of the spectral features.

In HH objects double peaked velocities have been observed through H_2 (see e.g., Davis & Smith 1996; Davis et al. 2000) or visible (e.g., Hartigan et al. 1986) high resolution spectroscopy which have been explained as a result of the hollow shell-like morphology of the bow shocks, since the near and far side of the bow shock shell, observed in projection, deflects material in the opposite directions (see e.g., Davis et al. 2001).

Both geometrical and physical bow shock models have been proposed to interpret optical and IR observations of HH objects (see e.g., Hartigan et al. 1987; Völker et al. 1999; Davis et al. 2001). In comparison with our observations, the broad slightly asymmetric profile measured in B3 and B4 (see Fig. 14) closely matches the $\text{H}\alpha$ theoretical profile calculated by Hartigan et al. (1987) for a bow shock with an inclination of 15° (that well fits our value of 13°), a shock velocity of 200 km s^{-1} , a temperature of 10^4 K and a pre-shock density of 300 cm^{-3} (for a comparison see their Fig. 3b).

On the contrary, the two velocity components in the B8 and R3 $1.644 \mu\text{m}$ line profiles cannot be explained in a bow shock context, because they do not seem to match with any model. Here the observed profiles could be explained in a framework of variable velocity mass ejection, where a fast moving jet reaches the preceding shock, slowed down by the medium at rest. This would explain the variability observed in the [Fe II] blue lobe velocity structure as well. In the case of knot B8 this hypothesis is confirmed by both the

Fig. 15. HH219 knot B8: 1.644 μm P-V diagram from slit 3 and multiepoch images. *Upper panel left:* contour plot image with slit 3 and 2 superimposed for comparison. *Right:* radial velocities derived from slit 3 corrected for the cloud speed with respect to the LSR. The slightly different PA ($\sim 8^\circ$) between the two slits well shows the presence of two distinct components, separated both in space and velocity. *Lower panel:* two epoch images of knot B8 (IRAC2b left, ISAAC binned right), showing changes in knot morphology and luminosity.

spectroscopic and the two epochs imaging observations. In fact, in the [Fe II] PV diagram of slit 3 (Fig. 15 upper panel), displaced with a PA slightly different ($\sim 8^\circ$) than that of slit 2, the two velocity components are clearly separated in both velocity and space. Moreover, the HVC spatially extends over the LVC, indicating that a faster jet, moving at a radial velocity of $\sim 110 \text{ km s}^{-1}$, is reaching a slower shocked region ($v_r \sim 25 \text{ km s}^{-1}$) from a slightly different direction with respect to the jet axis. This is likely confirmed by the fact that the HVC in slit 2 (along the axis) is not spatially split from the LVC. Also examining the two epoch images (Fig. 15 lower panel) the motion and the formation of a new bright condensation (namely B8) is quite evident comparing the ISAAC binned image (right side) with the previous IRAC2b image (left side).

Finally, regarding the fact that the H_2 high resolution spectroscopy does not show any double component of the velocity, due to the small inclination angle with respect to the sky, can be ascribed to the limited velocity resolution.

5. Conclusions

In this paper, we present an infrared study of the southern star forming region associated with IRAS 08211-4158 located in the Vela Molecular Clouds. The observational method (IR imaging and spectroscopy) addresses both the global properties of the stellar population and the mechanisms of the interactions between stars and interstellar medium. The main results of this work can be summarized as follows:

- Near IR imaging (with limiting magnitudes of $H \sim 18.2$, $K \sim 17.3$, $L \sim 15.2$ and $M \sim 12.5$) of a star forming region in VMR has provided a catalogue of 151 sources and indicates that a young cluster is present in the investigated region with a volume density of 3.8×10^4 stars per cubic parsec and an age of 10^6 – 10^7 yr.
- The central region of the cluster hosts the most massive and youngest object (IRS 8–2 or # 16), in whose neighbourhood a large fraction of sources with an IR excess are found. This suggests a sort of evolutionary segregation, with the less evolved stars lying towards the cluster’s center. This also implies a mass segregation and confirms that the most massive stars found in the clusters of VMR do not appear to form before the low mass ones.
- IRS 8–2 is a very young star of $642 L_\odot$ and $5\text{--}6 M_\odot$ (spectral type B2), which drives a previously known bipolar jet. While it is not surprising that the unique jet detected across the region is driven by the youngest object in the field, the detection of a jet driven by an intermediate mass star is quite uncommon, and confirms that the general characteristics of $\sim 1 L_\odot$ exciting sources are applicable to higher luminosity objects as well (at least up to about $600 L_\odot$).
- VLT spatial resolution allows us to investigate the jet structure in much more detail than our previous study. We have discovered 11 additional knots, two of which are very close to the exciting source ($\approx 2500 \text{ AU}$): they indicate that the outflow phenomenon is likely still ongoing.
- Through low resolution IR spectroscopy, spectra of the individual knots are obtained. The most prominent features are the H_2 vibrational transitions (up to $v = 4$) and the [Fe II] emission lines coming from the first 13 fine structure levels. Some other ionic lines such as the [C I], [S II] doublets and the He I ($1.083 \mu\text{m}$) are detected in a few knots. H_2 and [Fe II] lines present in both lobes of the jet (red-shifted and blue-shifted) have different morphologies and intensity ratios, indicating a complex structure with the high excitation lines preferentially concentrated along the jet axis.
- By comparing [Fe II] narrow band images taken in different epochs, the proper motion of a few knots can be inferred.

This permits an evaluation of the tangential velocity of the knots.

- High resolution spectroscopy gives the radial component of the knot velocity, thus both the total velocity values can be obtained (ranging around 300 km s^{-1}) and the jet inclination angle with respect to the plane of the sky ($i = 13^\circ \pm 4^\circ$)
- The [Fe II] line profiles are also resolved in a double-peaked structure which is consistent with the predictions of a bow-shock model (with $i = 15^\circ$) for almost all the observed features. Nevertheless, at least in one case (B8), the HV and LV components cannot be explained in a bow shock context, but in a framework of variable mass ejection, where a fast moving jet reaches the preceding one.
- We derive a dynamical age between 300 and 500 years for the observed knots in the blue lobe and a value of ~ 200 years for those in the red lobe.

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References

- Allen, C. W. 1976, *Astrophysical Quantities*, 3rd ed. (London: Athlone press)
- Benson, P. J., Myers, P. C., & Wright, E. L. 1984, *ApJ*, 279, L27
- Bouchet, P., Schmider, F. X., & Manfroid, J. 1991, *A&AS*, 91, 409
- Bragg, S. L., Smith, W. H., & Brault, J. W. 1982, *ApJ*, 263, 999
- Cabrit, S., & Bertout, C. 1992, *A&A*, 261, 274
- Carter, B. S., & Meadows, V. S. 1995, *MNRAS*, 276, 1052
- Cohen, M., & Schwartz, R. D. 1983, *ApJ*, 265, 877
- Chrysostomou, A., Hobson, J., Davis, C. J., Smith, M. D., & Berndsen, A. 2000, *MNRAS*, 314, 229
- Cuby, J.-G., Lidman, C., Johnson, R., & Moutou, C. 2003, *ISAAC User Manual*
- Davis, C. J., & Smith, M. D. 1996, *A&A*, 309, 929
- Davis, C. J., Berndsen, A., Smith, M. D., Chrysostomou, A., & Hobson, J. 2000, *MNRAS*, 314, 241
- Davis, C. J., & Eisloffel, J. 1995, *A&A*, 300, 851 (Erratum 305, 694 (1996))
- Davis, C. J., Hodapp, K. W., & Desroches, L. 2001, *A&A*, 377, 285
- Davis, C. J., Whelan, E., Ray, T. P., & Chrysostomou, A. 2003, *A&A*, 397, 693
- Erickson, G. W. 1977, *J. Phys. Chem. Ref. Data*, 6, 831
- Fuller, G. A., Zijlstra, A. A., & Williams, S. J. 2001, *ApJ*, 555, L125
- Giannini, T., Nisini, B., Caratti o Garatti, A., & Lorenzetti, D. 2002, *ApJ*, 570, L33
- Giannini, T., McCoey, C., Caratti o Garatti, A., et al. 2004, *A&A*, 419, 999
- Graham, J. A. 1991, *PASP*, 103, 79 (G91)
- Gredel, R. 1994, *A&A*, 292, 580
- Hartigan, P., Mundt, R., & Stocke, J. 1986, *AJ*, 91, 1357
- Hartigan, P., Raymond, J., & Hartmann, L. 1987, *ApJ*, 316, 323
- Hodapp, K., & Davis, C. J. 2002, *ApJ*, 575, 291
- Johansson, S. 1978, *Phys. Scr.*, 18, 217
- Koornneef, J. 1983, *A&A*, 128, 84
- Leinert, Ch., & Haas, M. 1989, *A&A*, 221, 110
- Lidman, C., Cuby, J.-G., & Vanzi, L. 2000, *Sofi User Manual*, ESO
- Liseau, R., Lorenzetti, D., Nisini, B., Spinoglio, L., & Moneti, A. 1992, *A&A*, 265, 577 (Paper I)
- Lorenzetti, D., Spinoglio, L., & Liseau, R. 1993, *A&A*, 275, 489 (Paper II)
- Lorenzetti, D., Giannini, T., Vitali, F., Massi, F., & Nisini, B. 2002, *ApJ*, 564, 839 (L02)
- Massi, F., Giannini, T., Lorenzetti, D., et al. 1999, *A&AS*, 136, 471 (Paper III)
- Massi, F., Lorenzetti, D., & Giannini, T. 2003, *A&A*, 399, 147 (Paper V)
- Massi, F., Lorenzetti, D., Giannini, T., & Vitali, F. 2000, *A&A*, 353, 598 (Paper IV)
- McGroarty, F., Ray, T. P., & Bally, J. 2004, *A&A*, 415, 189
- Najita, J., Carr, J. S., & Tokunaga, A. T. 1996, *ApJ*, 456, 292
- Nanda Kumar, M. S., Bachiller, R., & Davis, C. J. 2002, *ApJ*, 576, 313
- Nisini, B., Caratti o Garatti, A., Giannini, T., & Lorenzetti, D. 2002, *A&A*, 393, 1035 (N02)
- Nisini, B., Antonucci, S., & Giannini, T. 2004, *A&A*, 421, 187
- Nussbaumer, H., & Storey, P. 1988, *A&A*, 193, 327
- Oliva, E., Moorwood, A. F. M., & Danziger, I. J. 1990, *A&A*, 240, 453
- Panagia, N. 1973, *AJ*, 78, 929
- Palla, F., & Stahler, S. W. 1993, *ApJ*, 418, 414
- Palla, F., & Stahler, S. W. 1999, *ApJ*, 525, 772
- Persson, S. E., & Campbell, B. 1988, *AJ*, 96, 1019
- Reipurth, B., Yu, K. C., Heathcote, S., Bally, J., & Rodriguez, L. F. 2000, *AJ*, 120, 1449
- Rieke, G. H., & Lebofsky, M. J. 1985, *ApJ*, 288, 618
- Rousselot, P., Lidman, C., Cuby, J.-G., Moreels, G., & Monnet, G. 2000, *A&A*, 354, 1134
- Scarrott, S. M., Draper, P. W., Rolph, C. D., & Wolstencroft, R. D. 1992, *MNRAS*, 257, 485
- Schwartz, R. D., Schultz, A. S. B., Cohen, M., & Williams, P. M. 1995, *ApJ*, 446, 218
- Stanke, T. 2000, Ph.D. Thesis, Univ. of Postdam
- Thompson, R. I. 1984, *ApJ*, 283, 165
- Völker, R., Smith, M. D., Suttner, G., & Yorke, H. W. 1999, *A&A*, 343, 953
- Wilking, B. A., Lada, C. J., & Young, E. T. 1989, *ApJ*, 340, 823
- Wouterloot, J. G. A., & Brand, J. 1989, *A&AS*, 80, 149

Online Material

Table 3. H₂ (2.122 μ m) and [Fe II] (1.644 μ m) fluxes and positions of the new knots detected toward IRS 8 region.

ID	Size	$F(2.12 \mu\text{m}) \pm \Delta F$	$F(1.64 \mu\text{m}) \pm \Delta F$	$\alpha(2000.0)$			$\delta(2000.0)$		
	($''^2$)	($10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$)	($10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$)	($^{\text{h}}$	($^{\text{m}}$	($^{\text{s}}$)	($^{\circ}$	($'$	($''$)
<i>B0</i>	0.44	1.8 ± 0.1	1.8 ± 0.2	08	22	52.7	-42	08	12.2
<i>B8</i>	3.70	2.7 ± 0.3	8.3 ± 0.3	08	22	53.4	-42	08	40.1
<i>B9</i>	7.38	28 ± 1	7.1 ± 0.2	08	22	53.5	-42	08	43.4
<i>B10</i>	1.88	1.1 ± 0.1	6.2 ± 0.2	08	22	54.0	-42	08	49.4
<i>B11</i>	5.79	12 ± 1	2.0 ± 0.2	08	22	53.5	-42	08	43.4
<i>B12</i>	17.65	31 ± 1	6.1 ± 0.2	08	22	53.8	-42	08	34.8
<i>B13</i>	4.9	<0.7	4.1 ± 0.5	08	22	52.5	-42	08	06.1
<i>R0</i>	0.82	4.6 ± 0.4	2.8 ± 0.2	08	22	51.7	-42	07	40.5
<i>R7</i>	1.07	2.4 ± 0.1	2.8 ± 0.2	08	22	50.9	-42	07	18.6
<i>R8</i>	1.56	5.0 ± 0.4	4.3 ± 0.2	08	22	51.4	-42	07	33.4
<i>R9</i>	2.19	3.8 ± 0.3	2.7 ± 0.2	08	22	51.3	-42	07	39.7

Table 4. H₂ and [Fe II] observed lines in IRS 8 red lobe.

Line	$\lambda(\mu\text{m})$	$F \pm \Delta F (10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1})$			
H ₂ lines		R1	R2	R6 ^a	R9
1-0 S(9)	1.688	...	...	1.1 ± 0.3	...
1-0 S(7)	1.748	4.6 ± 0.5	1.4 ± 0.4	3.8 ± 0.5	1.6 ± 0.5
1-0 S(6)	1.788	3.8 ± 0.8	1.1 ± 0.4	3.2 ± 0.4	1.8 ± 0.7
1-0 S(3)	1.958	20 ± 3	8.5 ± 0.6	15 ± 4	8 ± 2
1-0 S(2)	2.034	7.6 ± 0.5	2.3 ± 0.4	7.3 ± 0.4	3.0 ± 0.9
3-2 S(5)	2.066	...	...	0.9 ± 0.3	...
2-1 S(3)	2.073	2.7 ± 0.4	1.2 ± 0.4	3.5 ± 0.5	...
1-0 S(1)	2.122	21.1 ± 0.6	4.9 ± 0.5	20 ± 0.5	6 ± 2
2-1 S(2)	2.154	2.5 ± 0.4	...	1.6 ± 0.5	...
3-2 S(3)	2.201	1.2 ± 0.4	...	1.8 ± 0.4	...
1-0 S(0)	2.223	6.8 ± 0.5	2.4 ± 0.6	6.0 ± 0.5	2.1 ± 0.5
2-1 S(1)	2.248	3.4 ± 0.8	1.4 ± 0.4	2.0 ± 0.5	1.5 ± 0.7^b
2-1 S(0)	2.355	...	1.1 ± 0.5^b	3 ± 1	...
3-2 S(1)	2.386	...	...	2.0 ± 0.5	...
1-0 Q(1)	2.407	20 ± 2	8 ± 2	14 ± 2	10 ± 3
1-0 Q(2)	2.413	11 ± 2	4 ± 2^b	11 ± 2	...
1-0 Q(3)	2.424	15 ± 3	6 ± 1	15 ± 3	...
1-0 Q(4)	2.437	10 ± 3	5 ± 1	7 ± 3	...
1-0 Q(5)	2.455	9 ± 3	11 ± 2	12 ± 4	...
1-0 Q(6)	2.476	9 ± 3	...	5 ± 1	...
1-0 Q(7)	2.500	16 ± 6	14 ± 5^b	21 ± 9^b	...

Line	$\lambda(\mu\text{m})$	$F \pm \Delta F (10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1})$				
[Fe II] lines		R1	R2	R6 ^a	R7	R9
$a^4\text{D}_{7/2} - a^6\text{D}_{9/2}$	1.257	2.4 ± 0.8	2.0 ± 0.4	...	0.8 ± 0.2	1.1 ± 0.3
$a^4\text{D}_{5/2} - a^4\text{F}_{9/2}$	1.534	...	...	2.5 ± 0.9^b	...	0.4 ± 0.2^b
$a^4\text{D}_{3/2} - a^4\text{F}_{7/2}$	1.600	...	...	1.4 ± 0.4	...	0.6 ± 0.2
$a^4\text{D}_{7/2} - a^4\text{F}_{9/2}$	1.644	4.4 ± 0.5	4.2 ± 0.5	10 ± 2	1.7 ± 0.4	2.6 ± 0.6
$a^4\text{D}_{5/2} - a^4\text{F}_{7/2}$	1.678	0.8 ± 0.4^b	...	1.8 ± 0.2	...	...
$a^4\text{D}_{7/2} - a^4\text{F}_{7/2}$	1.809	...	...	8 ± 4^b	...	...

Notes: for knot R7 1-0 S(1) ($2.122 \mu\text{m}$) flux is $0.6 \pm 0.2 (10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1})$.

^a Not observed with the blue grism.

^b S/N ratio between 2 and 3.

Table 5. H₂ observed lines in IRS 8 blue lobe.

Line	$\lambda(\mu\text{m})$	$F \pm \Delta F (10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1})$		
H ₂ lines		<i>B2</i>	<i>B3</i> ^a	<i>B6</i> ^b
2–0 S(9)	1.053	...	...	7 ± 1
2–0 S(7)	1.064	...	...	7 ± 1
2–0 S(6)	1.073	...	2.6 ± 0.6	6.9 ± 0.7
2–0 S(5)	1.085	...	10 ± 1 ^d	9.1 ± 0.6
2–0 S(4)	1.100	...	...	3.0 ± 0.9
2–0 S(3)	1.117	...	2.9 ± 0.5	5 ± 1
3–1 S(9)	1.122	...	3 ± 1	6 ± 1
3–1 S(8)	1.124	...	...	6 ± 2
3–1 S(7)	1.130	...	...	4 ± 2 ^c
2–0 S(2)+3–1 S(6)	1.138–1.140	...	...	11 ± 3
3–1 S(8)	1.152	...	...	4 ± 1
2–0 S(1)	1.162	...	1.9 ± 0.6	6 ± 1
3–1 S(8)	1.167	...	...	2.5 ± 0.9 ^c
3–1 S(3)	1.186	...	2 ± 1 ^c	4.0 ± 0.9
4–2 S(7)	1.205	...	...	1.4 ± 0.6 ^c
3–1 S(2)	1.207	...	...	2.5 ± 0.7
4–2 S(5)	1.226	...	1.6 ± 0.5	2.9 ± 0.8
3–1 S(1)	1.233	...	1.5 ± 0.5	3.7 ± 0.8
2–0 Q(1)	1.238	...	1.8 ± 0.5	4.9 ± 0.7
2–0 Q(2)	1.242	...	1.4 ± 0.4	3.4 ± 0.7
2–0 Q(3)	1.247	...	1.6 ± 0.5	5.5 ± 0.8
2–0 Q(4)	1.254	...	...	1.9 ± 0.5
4–2 S(3)+ 3–1 S(0)	1.261–1.262	...	2.5 ± 0.5	2.5 ± 0.5
2–0 Q(5)	1.263	...	...	3.2 ± 0.5
2–0 Q(7)	1.287	...	...	3.3 ± 0.7
4–2 S(1)	1.311	...	2.2 ± 0.5	4.0 ± 0.8
3–1 Q(1)	1.314	...	...	2.1 ± 0.5
3–1 Q(2)+2–0 Q(9)	1.319	...	...	2.5 ± 0.6
3–1 Q(3)	1.324	...	...	1.7 ± 0.7 ^c
2–0 O(3)	1.335	...	1.5 ± 0.5	5.6 ± 0.9
3–1 Q(5)+4–2 S(0)	1.342	...	4 ± 1	5 ± 1

Notes: ^a Knot *B3* partially includes knot *B4* emission.^b Knot *B6* partially includes knot *B12* emission.^c S/N ratio between 2 and 3.^d Blend of 2–0 S(5) and He I.

Table 5. continued.

Term	$\lambda(\mu\text{m})$	$F \pm \Delta F$ (10^{-15} erg cm $^{-2}$ s $^{-1}$)		
H ₂ lines		<i>B2</i>	<i>B3</i> ^a	<i>B6</i> ^b
3–1 O(3)	1.522	...	...	3.1 ± 0.8
1–0 S(10)	1.666	...	...	1.2 ± 0.4
1–0 S(9)	1.688	...	1.9 ± 0.4	5.6 ± 0.5
1–0 S(8)	1.714	...	1.6 ± 0.3	3.9 ± 0.4
1–0 S(7)	1.748	0.7 ± 0.2	6.9 ± 0.4	19.9 ± 0.4
1–0 S(6)	1.788	0.8 ± 0.2	4.5 ± 0.6	17.2 ± 0.7
1–0 S(3)	1.958	10 ± 1	57 ± 4	151 ± 2
2–1 S(4)	2.004	...	3.8 ± 0.6	7 ± 1
3–2 S(6)	2.013	...	1.8 ± 0.6	3 ± 1
1–0 S(2)	2.034	3.8 ± 0.6	16.5 ± 0.6	46 ± 1
3–2 S(5)	2.066	...	1.2 ± 0.4	4 ± 1
2–1 S(3)	2.073	1.3 ± 0.6^c	6.1 ± 0.6	19 ± 1
1–0 S(1)	2.122	6.8 ± 0.4	35.6 ± 0.7	98 ± 2
2–1 S(2)	2.154	...	3.8 ± 0.4	8.4 ± 0.5
3–2 S(3)	2.201	...	1.8 ± 0.3	4.4 ± 0.7
1–0 S(0)	2.223	3.7 ± 0.4	11.3 ± 0.3	31.6 ± 0.9
2–1 S(1)	2.248	2.9 ± 0.7	7.5 ± 0.5	20.6 ± 0.9
2–1 S(0)	2.355	4 ± 2^c	3.0 ± 1.0	11 ± 3
3–2 S(1)	2.386	4 ± 2^c	6 ± 2	9 ± 3
1–0 Q(1)	2.407	15 ± 4	58 ± 2	144 ± 4
1–0 Q(2)	2.413	...	39 ± 3	85 ± 4
1–0 Q(3)	2.424	...	44 ± 3	102 ± 4
1–0 Q(4)	2.437	...	39 ± 4	88 ± 5
1–0 Q(5)	2.455	...	...	32 ± 4
1–0 Q(6)	2.476	...	20 ± 9^c	...
1–0 Q(7)	2.500	...	60 ± 30^c	...

Notes: ^a Knot *B3* partially includes knot *B4* emission.^b Knot *B6* partially includes knot *B12* emission.^c *S/N* ratio between 2 and 3.

Table 6. [Fe II] observed lines in IRS 8 blue lobe.

Line	$\lambda(\mu\text{m})$	$F \pm \Delta F (10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1})$		
[Fe II] lines		<i>B2</i>	<i>B3</i> ^a	<i>B6</i> ^b
$a^4\text{D}_{7/2}-a^6\text{D}_{9/2}$	1.257	0.9 ± 0.3	22.8 ± 0.3	25.4 ± 0.5
$a^4\text{D}_{3/2}-a^6\text{D}_{3/2}$	1.279	...	2.2 ± 0.5	1.3 ± 0.6^c
$a^4\text{D}_{5/2}-a^6\text{D}_{5/2}$	1.295	...	3.1 ± 0.4	2.4 ± 0.8
$a^4\text{D}_{7/2}-a^6\text{D}_{7/2}$	1.321	...	8.8 ± 0.4	9.9 ± 0.7
$a^4\text{D}_{5/2}-a^6\text{D}_{3/2}$	1.328	...	1.9 ± 0.9^c	2.2 ± 0.8^c
$a^4\text{D}_{5/2}-a^4\text{F}_{9/2}$	1.534	...	1.8 ± 0.3	2.7 ± 0.7
$a^4\text{D}_{3/2}-a^4\text{F}_{7/2}$	1.600	...	1.5 ± 0.5	2.4 ± 0.6
$a^4\text{D}_{7/2}-a^4\text{F}_{9/2}$	1.644	1.0 ± 0.2	22.7 ± 0.4	22.7 ± 0.7
$a^4\text{D}_{1/2}-a^4\text{F}_{5/2}$	1.664	...	1.4 ± 0.5^c	1.6 ± 0.5
$a^4\text{D}_{5/2}-a^4\text{F}_{7/2}$	1.678	...	2.6 ± 0.6	2.2 ± 0.5
$a^4\text{D}_{3/2}-a^4\text{F}_{5/2}$	1.711	...	0.9 ± 0.4^c	...
$a^4\text{D}_{3/2}-a^4\text{F}_{3/2}+a^4\text{D}_{5/2}-a^4\text{F}_{5/2}$	1.800	...	2.4 ± 0.4	...
$a^4\text{D}_{7/2}-a^4\text{F}_{7/2}$	1.809	...	1.3 ± 0.6^c	7 ± 3^c
Other ionic lines				
[C I] $^1\text{D}_2-^3\text{P}_1$	0.983	2.5 ± 0.9^c	5 ± 1	4.6 ± 0.6
[C I] $^1\text{D}_2-^3\text{P}_2$	0.985	3 ± 1	7 ± 1	10.2 ± 0.5
He I $^3\text{S}-^3\text{P}^\circ$	1.083	...	10 ± 1^d	6.9 ± 0.7
[S II] $^2\text{P}_{3/2}-^2\text{D}_{3/2}$	1.029	...	4 ± 1	...
[S II] $^2\text{P}_{3/2}-^2\text{D}_{5/2}^e$	1.032	...	3 ± 1	7 ± 3^c
Pa γ	1.094	...	1.7 ± 0.5	4 ± 1
Pa β	1.283	...	2.1 ± 0.7	4 ± 1

Notes: ^a Knot *B3* partially includes knot *B4* emission.^b Knot *B6* partially includes knot *B12* emission.^c *S/N* ratio between 2 and 3.^d Blend of 2–0 S(5) and He I.^e Blended with [S II] $^2\text{P}_{1/2}-^2\text{D}_{3/2}$.