Molecular jets driven by high-mass protostars: a detailed study of the IRAS 20126+4104 jet*

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Received 5 February 2008 / Accepted 13 March 2008

ABSTRACT

Context. Protostellar jets from intermediate- and high-mass protostars provide an excellent opportunity to understand the mechanisms responsible for intermediate- and high-mass star-formation. A crucial question is if they are scaled-up versions of their low-mass counterparts. Such intermediate- and high-mass jets are relatively rare and, usually, they are distant and highly embedded in their parental clouds. The IRAS 20126+4104 molecular jet, driven by a $10^4 M_\odot$ protostar, represents a suitable target to investigate.

Aims. We present here an extensive analysis of this protostellar jet, deriving the kinematical, dynamical, and physical conditions of the H$_2$ gas along the flow.

Methods. The jet was investigated by means of near-IR H$_2$ and [Fe II] narrow-band imaging, high-resolution spectroscopy of the 1–0 S(1) line (2.12 $\mu$m), NIR (0.9–2.5 $\mu$m) low-resolution spectroscopy, along with ISO-SWS and LWS spectra (from 2.4 to 200 $\mu$m).

Results. The flow shows a complex morphology. In addition to the large-scale jet precession presented in previous studies, we detect a small-scale wiggling close to the source, which may indicate the presence of a multiple system. The peak radial velocities of the H$_2$ gas range from ~42 to ~14 km s$^{-1}$ in the blue lobe, and from ~8 to 47 km s$^{-1}$ in the red lobe. The low-resolution spectra are rich in H$_2$ emission, and relatively faint [Fe II] (NIR), [O I] and [C II] (FIR) emission is observed in the region close to the source. A warm H$_2$ gas component has an average excitation temperature that ranges between 2000 K and 2500 K. Additionally, the ISO-SWS spectrum reveals a cold component (520 K) that strongly contributes to the radiative cooling of the flow and plays a major role in the dynamics of the flow. The estimated $L_{H_2}$ of the jet is $8.2 \pm 0.7 L_\odot$, suggesting that IRAS 20126+4104 has a significantly increased accretion rate compared to low-mass YSOs. This is also supported by the derived mass flux rate from the H$_2$ lines ($M_{\text{acc}}(\text{H}_2) \sim 7.5 \times 10^{-4} M_\odot$ yr$^{-1}$).

The comparison between the H$_2$ and the outflow parameters strongly indicates that the jet is driving the outflow, at least partially. As already found for low-mass protostellar jets, the measured H$_2$ outflow luminosity is tightly related to the source bolometric luminosity.

Conclusions. As for a few other intermediate- and high-mass protostellar jets in the literature, we conclude that IRAS 20126+4104 is a scaled-up version of low-mass protostellar counterparts.

Key words. stars: pre-main-sequence – infrared: ISM – ISM: jets and outflows – ISM: kinematics and dynamics – individual objects: IRAS 20126+4104

1. Introduction

Protostellar jets and outflows are a ubiquitous phenomenon among young stellar objects (YSOs) of different masses and luminosities (see e.g. Shepherd 2003). They are usually explained as a consequence of accretion from a disc around the protostar (see e.g. Pudritz & Norman 1986; Camenzind 1990). This is particularly true for low- and, partially, for intermediate- and high-mass YSOs up to $L_{\text{bol}} \sim 10^4 L_\odot$ (or spectral type B0), where collimated outflows, often driven by protostellar jets, have been observed (Shepherd 2003). In contrast, no highly collimated outflow or circumstellar disc has been observed in high-mass protostars exceeding $10^5 L_\odot$ (or O-type stars, the spectral type and $L_{\text{bol}}$ of the M17 disc silhouette are not clear yet) (see e.g. Arce et al. 2007; Zinnecker & Yorke 2007), and the formation mechanism of these latter objects is still being debated. The observations are, however, strongly limited by the large distance of the massive star-forming regions, the considerable extinction, and the short lifetime of massive YSOs. In addition, these objects are often grouped in small clusters, which confuses the morphology of massive star-forming regions even more. Therefore, optical and IR studies of intermediate-high-mass protostellar jets are very rare, and only a few examples are present in the literature: e.g. IRAS 18162-2048 ($L_{\text{bol}} \sim 2 \times 10^4 L_\odot$, Martí et al. 1995), IRAS 20126+4104 ($L_{\text{bol}} \sim 10^4 L_\odot$, Ayala et al. 1998), IRAS 16547-4247 ($6 \times 10^4 L_\odot$, Brooks et al. 2003), IRAS 18151-1208 ($2 \times 10^3 L_\odot$, Davis et al. 2004), and IRAS 11101-5829 ($10^4 L_\odot$, Gredel 2006), the M17 disc silhouette ($M_{\text{YSO}} \sim 15 M_\odot$, Nürnberger et al. 2007). Expanding the number of observations of intermediate- and high-mass jets and comparing their general properties with those of low-mass protostellar jets is therefore important for understanding whether differences exist, or if high-mass protostellar jets are just scaled up versions of their low-mass counterparts. We therefore investigated the kinematical and physical properties of the IRAS 20126+4104 jet by means of NIR narrow-band imaging.
high-resolution and low-resolution IR spectroscopy. We then compared our findings with those of other high- and low-mass protostellar jets available in the literature.

IRAS 20126+4104, at a distance 1.7 kpc, is a very well studied high-mass YSO (M ∼ 7 M⊙, Cesaroni et al. 1997, 2005) in a very early stage of evolution. It is accreting mass at a very high rate (Macc ∼ 2 × 10^{-3} M⊙ yr^{-1}, Cesaroni et al. 2005) and it gives birth to a large poorly-collimated CO outflow. It harbours the first H2 jet detected from a high mass YSO (Ayala et al. 1998), which had previously been seen in SiO emission close to the source (Cesaroni et al. 1999). The H2 jet extends for about 1 pc. Its “S” shape morphology suggests that it is precessing with a period of ∼60 000 yr and with a wide precession angle of about 37° (Shepherd et al. 2000). As a consequence, the inclination of the flow with respect to the plane of the sky changes strongly from ∼9°, close to the source, up to ∼45° in the outer part of the flow.

The structure of this paper is as follows. In Sect. 2 our observations are presented. Section 3 reports an overview of our results, including the morphology of the H2 jet, its kinematics, the physical parameters of the gas, its energy, and mass flux rate. In Sect. 4 we briefly consider the cause of the newly detected small-scale precession mode. Then, we discuss our H2 data in relation to the CO outflow literature data. Finally, we compare the properties of the IRAS 20126+4104 jet with other high- and low-mass protostellar jets.

2. Observations and data reduction

Our data were collected at the UK Infrared Telescope (UKIRT), and at the 3.5 m Italian Telescopio Nazionale Galileo (TNG). More data were retrieved from the Subaru and ISO archives1. The relevant information on the observational settings is summarised in Table 1.

2.1. Imaging: H2 and [Fe II]

We used narrow-band filters centred on the H2 (2.12 μm) and [Fe II] (1.64 μm) lines to detect both molecular and ionic emission along the flow. Additional broad-band images (H and K') were gathered to remove the continuum. Our images were collected at UKIRT, using the near-IR instrument UIST (Ramsay Howat et al. 2004) ([Fe II], H), and at the TNG, using NICS (Baffa et al. 2001) (H2, K'). All the raw data were reduced using IRAF2 packages, applying standard procedures for sky subtraction, dome flat-fielding, bad pixel and cosmic ray removal, and image-mosaicking. The resulting mosaics cover a region around IRAS 20126+4104 of 3:4 × 3:4 for UIST and 5:6 × 5:6 for NICS. The calibration for both instruments was obtained by means of photometric standard stars observed in both narrow- and broad-band filters. In the calibrated and continuum-subtracted narrow-band images, we measured H2 and [Fe II] fluxes for each detected knot using the task polyphot in IRAF, defining each region within a 3σ contour level above the sky background.

Additional high-resolution, narrow-band images (H2, Brγ, and Kcont) of the central part of the molecular flow (∼35″ × 35″)

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1 These data are available at http://smoka.nao.ac.jp/ (Subaru), and http://www.iso.vilspa.esa.es/ida/index.html (ISO).

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.

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were retrieved from the Subaru data archive (Baba et al. 2002). The set of data were taken with the Coronagraphic Imager with Adaptive Optics (CIAO) (Murakawa et al. 2003), used as a high-resolution NIR imager (0′′.022/pixel). These data were used for a morphological study of the flow only close to the source (see Sects. 3.1 and 4.1).

Finally, we used K-band stars from the Two Micron All Sky Survey (2MASS) for the astrometric calibration of all the images. As a result the formal errors for the plate solutions are ∼0′′.5, 0′′.4, and 0′′.2, for the NICS, UIST, and CIAO images, respectively.

2.2. Spectroscopy

2.2.1. Low-resolution spectroscopy

The NIR low-resolution spectroscopy (R ~ 500, slit width 1″) was acquired with NICS during two runs at the TNG, using three different grisms covering all the full NIR spectrum (0.9–2.5 μm) (see Table 1). The position of the slits is shown in Fig. 1. Slits 1 and 3 are positioned on the knots close to the source (knots A, B, and C) and parallel to the jet axis, covering almost all the H2 emitting area. Slits 2 and 4 encompass the so-called “jet” (see Ayala et al. 1998), that is the farthest H2 emission in the red lobe (see also Fig. 1).

To perform our spectroscopic measurements, we adopted the usual ABB’A’ configuration, with a total integration time between 1800 s and 2400 s per grism per slit. Each observation was flat fielded, sky subtracted and corrected for the curvature caused by longslit spectroscopy, while atmospheric features were removed by dividing each spectrum by a telluric standard star (spectral O type). The wavelength calibration was obtained from Xenon and Argon lamps. The flux was calibrated observing the photometric standard star AS 35–0 (Hunt et al. 1998). As the
Table 1. Journal of observations.

<table>
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<th>Date of obs (d.m.y)</th>
<th>Telescope/Instrument</th>
<th>Filler</th>
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<th>Seeing (″)</th>
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<tr>
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<td>UKIRT/CIAS</td>
<td>H</td>
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<td>0.6</td>
<td>360</td>
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<tr>
<td>06.08.2006</td>
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<td>1.2</td>
<td>900</td>
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<tr>
<td>06.08.2006</td>
<td>TNG/NICS</td>
<td>K′</td>
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<td>1.2</td>
<td>90</td>
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<td>10.07.2003</td>
<td>Subaru/CIAO</td>
<td>H₂, Brγ, Kcont</td>
<td>0.022</td>
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<td>1800</td>
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</table>

used grisms overlap between ~1.1 and 1.8 μm (see Table 1), the single spectra were combined to obtain deeper spectra. Finally, since no substantial difference was found between the pairs of spectra from Slits 1 and 3, or from Slits 2 and 4, they were combined together to get a deeper spectrum for each observed knot.

2.2.2. High-resolution spectroscopy

Our H₂ 1–0S(1) (λ_{vac} = 2.1218356 μm; Bragg et al. 1982) echelle spectra were obtained at UKIRT using the spectrometer CGS4 (Mountain et al. 1990) (see Table 1), equipped with a 256×256 pixel InSb array (0.41×0.90 pixel scale, in the dispersion and spatial direction, respectively). A 1-pixel-wide slit was used, resulting in a velocity resolution of ~7.4 km s⁻¹ pixel⁻¹ and corresponding to a nominal resolving power of ~18 500. The instrumental profile in the dispersion direction, measured from Gaussian fits to the OH sky lines, was ~10.9 km s⁻¹ (or 1.46 Å).

The targets and position angles (PAs) of the four slits are reported in Table 1, while the slit positions are shown in Fig. 1 and encompass all the H₂ knots of the flow. Slits 1 and 2 are parallel to the flow axis and positioned on the knots close to the source (knots A, B, and C). Slat 3 encompasses the so-called “jet”, and Slat 4 encompasses knot D and partially knot C. The total exposure time for each position is 2700 s.

The raw spectra were wavelength-calibrated using the bright OH lines (Roussetlot et al. 2000) detected on each frame. The employed IRAF tasks (identify, re-identify, fitcoords, and transform) also correct for the spatial distortion, and a 3rd-order fit in two dimensions has been used. As a result, the calibration is accurate to ~3 km s⁻¹. The spectra were not flux-calibrated.

2.2.3. ISO data archive

Mid-IR and far-IR spectra of the flow were retrieved from the ISO satellite Data Archive, in the form of Highly Processed Data Product (HPDP set 35500738, by Frieswijk et al.; HPDP set 04300333 by Lloyd, Lerate, and Grundy). The first set of data (from 2.38 to 45.2 μm, see also Table 1) was taken with the Short Wavelength Spectrometer (SWS, de Graauw et al. 1996) in the AOT01 grating mode (R = 1000–2000), and is centred on the IRAS source covering a region of 33″ × 20″. The covered FoV is shown in Fig. 1. The second set of data (from 43 to 197 μm) was taken with the Long Wavelength Spectrometer (LWS, Clegg et al. 1996) in the AOT01 grating mode (R = 200), and is positioned ~48″ north of the source. With a beam of 80″ it covers large parts of the flow, except the so-called “jet”.

3. Results

3.1. H₂ and [Fe II] imaging

An overview of the large-scale morphology of the H₂ flow is given in Fig. 1. The emission in the SE, the so-called “jet”, appears to be composed of four different knots, labelled knots 1 to 4 (see Sect. 3.3). No other knots were detected SE or NW up to ~2.8 (or ~1.4 pc) from the source, down to a 3σ limit of ~8×10⁻¹⁷ erg s⁻¹ cm⁻² arcsec⁻².

A new emission feature, labelled X (α(J2000) = 20°14'26.1" and δ(J2000) = 41°13'32.4"), has been detected close to the position of the IRAS source. Figure 2 shows a close-up in H₂ of the source position and the new knot, located in the redshifted lobe. The circle represents the formal error for the NICS plate solution centred on the IRAS source position (Hofner et al. 2007). Contours of the [Fe II] emission are superimposed on this image as well. The two stars in the field have been used to match the H₂ and [Fe II] images ex-
The positions of the new knot X, knot B, the source, and two field stars are also indicated. The morphology of the H$_2$ flow close to the source. In Fig. 2. Close-up of the H$_2$ image around the presumed source position (Hofner et al. 2007, see also the caption of Fig. 1) indicated by a circle (the radius represents the formal error for the NICS plate solution). [Fe II] contours (5 in red, 30 in yellow, 50, 60, 70, 80, 100 $\times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) are overlaid on the image. The positions of the new knot X, knot B, the source, and two field stars are also indicated.

Actually, both our H$_2$-K' and [Fe II]-H data (as well as the spectroscopic data, see Sect 3.2) indicate that the emission of this knot arises from a shock. Remarkably, the knot overlaps with one of the bipolar features (located SE of the source) detected in the K-band by Sridharan et al. (2005). No other [Fe II] emission has been detected along this flow, down to a 3-$\sigma$ limit of $\sim 3 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ or along the blue lobe at the position where an H$_{\alpha}$ and [S II] emitting knot was observed by Shepherd et al. (2000).

The higher angular resolution of Subaru images delineates details of the morphology of the H$_2$ flow close to the source. In Fig. 3 we show the continuum-subtracted H$_2$ image. The Br$\gamma$ image turned out to be more efficient than the $K_{\text{cont}}$ image in removing the strong continuum detected on the knots. Its use is justified by the absence of any Br$\gamma$ emission in the observed knots (see Sect. 3.2). Scattered H$_2$ emission would, of course, not be subtracted by this procedure. The H$_2$ flow wiggles noticeably with an opening angle of $\sim 16^\circ$ around an axis with PA of $\sim 61^\circ$. This fully agrees with SiO radial velocity observations (Cesaroni et al. 1999; Su et al. 2007), which revealed a precessing jet with an opening cone of $21^\circ$, PA $\sim 60^\circ$, and an inclination of 9$^\circ$ with respect to the plane of the sky. This small-amplitude precession seems to be superimposed on the larger one observed on a large scale (Shepherd et al. 2000; Cesaroni et al. 2005; see also Fig. 1).

In the blue lobe (see Fig. 3) knot B appears composed of a faint jet (feature 1) ending in a bow shock (2), which is preceeded by two smaller bow shocks (3). Further ahead, knot C consists of at least two bright structures. In the red lobe, the new knot X is visible as well, and, further out, knot A appears fragmented in 2–3 sub-structures.

### 3.2. Low-resolution spectroscopy

#### 3.2.1. Low-resolution – TNG

From our four TNG slits, we derived low-resolution spectra of six knots, namely A, B, C, and X close to the source, and knots 1 and 4 along the “jet”. All these spectra are rich in H$_2$ emission. Remarkably, no ionic emission is detected along the flow, with the exception of faint [Fe II] emission in knot X (also observed in the narrow-band image) and in knot B (below the detection limit of our imaging). It is worth noting that the ratio between the H$_2$ lines (see, e.g., 2.12 $\mu$m) and the [Fe II] lines changes in the observed knots. Continuum emission from the regions enclosing knots A and B is observed in the $K$ band.

The lines detected in the spectra, along with their vacuum wavelengths and fluxes (uncorrected for the extinction), are presented in Table 2. Line fluxes were obtained by fitting the profile with a single or double Gaussian in case of blending. The uncertainties associated with these data derive only from the rms of the local baseline multiplied by the linewidths. Lines showing fluxes with $S/N$ ratio between 2 and 3 have been labelled in the table.

Figure 4 shows the spectrum of knot C, the brightest one observed. Only H$_2$ lines are visible from 1 to 2.5 $\mu$m, involving vibrational levels from $v = 1$ up to $v = 5$ (coming from energy levels from 6000 K up to 30 000 K). The presence of lines from high-$v$ levels (i.e. with high excitation energies) indicates a high excitation of the gas. In the remaining knots, we identify H$_2$ emission lines up to $v \leq 3$, mostly detected in the $H$- and $K$-bands (except for a few $v = 2$ lines from the $J$-band observed in knot B).

Considering both the combined effects of the knot morphologies and the slit positions, there is excellent agreement between the photometric fluxes in our images and the fluxes measured in our spectra for both [Fe II] (1.64 $\mu$m) and H$_2$ (2.12 $\mu$m) lines.
3.2.2. Low resolution – ISO

Table 3 lists the lines identified in the ISO-SWS and ISO-LWS spectra, their vacuum wavelengths and integrated fluxes, estimated from Gaussian fits to the (unresolved) line profiles, together with the error from the rms noise of the local baseline. Due to the large FoV of the two instruments, it is impossible to determine the spatial extension of the emitting region, thus the measured fluxes can originate from any or all of the different knots (A...D) close to the source. Several emission lines are detected, superimposed on a strong continuum observed in both SWS and LWS spectra. The detected lines are shown in Fig. 5. The H$_2$ lines from the $v = 1$ and $v = 0$ levels have been detected between 2.4 and 17 $\mu$m. In particular, the 1–0 Q lines (also observed in our NIR spectra), the 1–0 O lines, and the 0–0 S lines, which usually trace the coldest component of the H$_2$ flow (see e.g., Froebrich et al. 2002; Giannini et al. 2004, 2006) were detected. In addition, two bright ionic lines were observed in the LWS spectrum, namely [O I] at 63 $\mu$m and [C II] at 158 $\mu$m. The origin of these lines is indeed intriguing, because no strong ionic emission lines were detected in the NIR. Possibly, they could originate from the same spot where [Fe II] is detected, and/or in a deeply embedded region (close to the source) not visible at NIR wavelengths, because our spectra do not show any evidence of the bright [C I] doublet at 1 $\mu$m, often detected in low-mass jets (see e.g. Nisini et al. 2002; Giannini et al. 2004). However, a more convincing explanation is that these lines are not arising from the shocks, but from a photo-dissociation region (PDR) around the massive object. Indeed, from the [O I](63 $\mu$m)/[C II](158 $\mu$m) ratio, we can distinguish between the two scenarios (see e.g., Hollenbach & McKee 1989). For intensity ratios below 10, the PDR origin is favoured. In our LWS spectrum this ratio is close to 1.

3.3. High resolution spectroscopy

In Table 4 we report the results of the high-resolution H$_2$ spectroscopy. For each knot in each slit we indicate the H$_2$ radial velocities ($v_{\text{LSR}}$), corrected for the cloud speed with respect to the LSR ($v_{\text{LSR}} = -3.5$ km s$^{-1}$, Cesaroni et al. 1997). Two or more velocity components are given where detected. The first reported value is the peak value. The last column gives the full width at zero intensity (FWZI) of the line profile, measured where the flux reaches a 2$\sigma$ background noise level (see e.g. Davis et al. 2001).

Position-velocity ($P – V$) diagrams are presented in Fig. 6 (CGS4 Slits 1 and 2) and in Fig. 7 (CGS4 Slits 3 and 4). In Fig. 8 the emission line profiles are shown. It is worth noting that our spectra often cannot resolve the single structures inside the wiggling jet, due to the limited spatial resolution. As a result, radial velocities are often an average over more than one substructure visible in the Subaru image.

Almost all the knots also have more than one velocity component in their spectral line profile, depending on the position of the slit with respect to the knot. However, such components are never completely resolved (with the exception of knot 2 along the “jet”, see Fig. 8), but they instead show up like “bumps” along the smooth profile. When single-peaked profiles are observed, the lines are never symmetric, but evidence of extended line-w wing emission (opposite to the blue- or redshifted peak) is always detected. This may be indicative of a bow shock morphology of the knots, producing both the wings and the different velocity components (see e.g. Davis et al. 2001; Schultz et al. 2005), as also indicated by the sub-millimetric observations of Su et al. (2007). Remarkably, knot B has four velocity components (see Table 4 and Fig. 8). The fourth component located at $\sim$64 km s$^{-1}$, and visible along the profile as a “bump” on the redshifted wing (see also knot X profile) cannot be explained in a bow shock context. This component could originate from a different flow, but we have no further evidence in support of this hypothesis.

The flux peaks of the knots range from $-42$ to $-14$ km s$^{-1}$ in the blue lobe, and from $-8$ to $47$ km s$^{-1}$ in the red lobe (see also Table 4). Noticeably, knots X and A in the red lobe (Fig. 6, central panel) have a slightly negative peak velocity. This can be understood by considering that close to the source the axis of the flow has an inclination of $\sim 9^\circ$ with respect to the plane of the sky, and the aperture angle of the precessing jet is $\sim 37^\circ$. Consequently, even if the knots are located in the “red” lobe, they could have a negative $v_{\text{FWZI}}$ (see also Su et al. 2007).

In both lobes, the absolute peak radial velocities of knots close to the source (A...C) are lower (0–30 km s$^{-1}$) than those located at greater distances (knot D and knots 1...4, 40–50 km s$^{-1}$). On the other hand, the FWZI of the line profiles decreases with distance (see Table 4 and Fig. 8). The line profiles of the knots close to the source are broader on average (110–180 km s$^{-1}$) than those far from the source (70–90 km s$^{-1}$). This could confirm that the inclination of the flow axis (with respect to the plane of the sky) is different in the two regions; i.e., it changes from $\sim 9^\circ$, close to the source, to $\sim 45^\circ$ further out, at knot 1...4 and knot D. On a smaller scale, radial velocities appear to oscillate. This is very visible in $P – V$ diagrams of Slit 3, and marginally, for the redshifted knots in Slit 1.

Assuming two different values for the inclination, the spatial velocity of the knots ranges between 50 and 80 km s$^{-1}$.

3.4. Physical parameters of the gas

The wealth of molecular hydrogen lines detected in both MIR and NIR spectra allows us to perform a detailed study of the H$_2$ excitation in a high-mass jet, also taking the pure rotational lines into account, for the first time.

As a result, employing all the available H$_2$ ratios in our ro-vibrational diagrams, we have derived column densities, extinction, and temperature of the gas. Combining these parameters with the 2.12 $\mu$m flux obtained from the narrow-band imaging, we determined an accurate measurement of the H$_2$ luminosity ($L_{H_2}$) for each knot and for the entire flow (see Caratti o Garatti et al. 2006 for a detailed description of this procedure).

3.4.1. Ro-vibrational diagrams from NIR lines

As a first step in our analysis, we only employed the NIR lines. Line pairs originating from the same energy level should lie in the same position of the ro-vibrational diagram. By varying the extinction value ($A_v$) and increasing the goodness of the fit (maximising the correlation coefficient), extinction and temperature can be evaluated simultaneously (see e.g. Giannini et al. 2004; Davis et al. 2004; Caratti o Garatti et al. 2006). To reduce the uncertainties, only the transitions with $S/N > 3$ and not affected by blending with other lines were used. The result of this analysis is shown in Table 5, where the average excitation temperature, the $A_v$, and the column densities of the warm gas component are listed for each knot (Cols. 2–4). The ro-vibrational diagrams are shown in Fig. 9.

To compute the extinction in each knot, we selected all the available pairs of lines. From the spectrum of knot C 41 lines were used, giving 29 different ratios (i.e.}$
<table>
<thead>
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<th>Term</th>
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<th>$F \pm \Delta F (10^{-15} \text{erg cm}^{-2} \text{s}^{-1})$</th>
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</thead>
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<td>2–0 S(9)</td>
<td>1.053</td>
<td>A: ... B: ... C: ... X: ... knot 1-jet: ... knot 4-jet: ...</td>
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</table>
| 2–0 S(8)     | 1.057             | ... ... 0.9 ± 0.3 ... ... ... ...
| 2–0 S(7)     | 1.064             | 2.8 ± 0.4 ... ... ... ...
| 2–0 S(6)     | 1.073             | 1.6 ± 0.4 ... ... ... ...
| 2–0 S(5)     | 1.085             | 3.5 ± 0.4 ... ... ... ...
| 2–0 S(4)     | 1.100             | 1.8 ± 0.3 ... ... ... ...
| 2–0 S(3)     | 1.117             | 1.3 ± 0.4 4.3 ± 0.2 ... ... ...
| 3–1 S(9)+3–1 S(10) | 1.120       | ... 2.0 ± 0.2 ... ... ...
| 3–1 S(8)     | 1.122             | 1.0 ± 0.3 ... ... ... ...
| 3–1 S(7)     | 1.125             | 0.7 ± 0.2 ... ... ... ...
| 3–1 S(6)     | 1.130             | 1.4 ± 0.2 ... ... ... ...
| 3–1 S(5)     | 1.132             | 0.5 ± 0.2 ... ... ... ...
| 2–0 S(5)     | 1.138             | 2.0 ± 0.2 ... ... ... ...
| 3–1 S(6)     | 1.140             | 0.7 ± 0.2 ... ... ... ...
| 3–1 S(5)     | 1.152             | 1.9 ± 0.3 ... ... ... ...
| 2–0 S(1)     | 1.162             | 1.3 ± 0.4 3.5 ± 0.3 ... ... ...
| 3–1 S(1)     | 1.167             | 1.2 ± 0.3 ... ... ... ...
| 3–1 S(0)     | 1.186             | 2.5 ± 0.3 ... ... ... ...
| 2–0 S(9)+4–2 S(10) | 1.189±1.190 | ... 0.9 ± 0.2 ... ... ...
| 4–2 S(9)+4–2 S(8) | 1.196±1.199 | ... 0.7 ± 0.2 ... ... ...
| 4–2 S(7)     | 1.205             | 1.1 ± 0.2 ... ... ... ...
| 3–1 S(2)     | 1.207             | 0.9 ± 0.2 ... ... ... ...
| 4–2 S(6)     | 1.214             | 0.6 ± 0.2 ... ... ... ...
| 4–2 S(5)     | 1.226             | 1.4 ± 0.2 ... ... ... ...
| 3–1 S(1)     | 1.233             | 1.4 ± 0.2 ... ... ... ...
| 2–0 Q(1)     | 1.238             | 0.6 ± 0.3: 2.6 ± 0.2 ... ... ...
| 2–0 Q(2)+4–2 S(4) | 1.242+1.242 | ... 1.4 ± 0.2 ... ... ...
| 2–0 Q(2)     | 1.247             | 0.9 ± 0.4: 2.8 ± 0.2 ... ... ...
| 2–0 Q(4)     | 1.254             | 1.1 ± 0.2 ... ... ... ...
| 4–2 S(3)+3–1 S(0) | 1.261       | ... 2.7 ± 0.3 ... ... ...
| 2–0 Q(5)     | 1.263             | 2.1 ± 0.3 ... ... ... ...
| 2–0 Q(6)     | 1.274             | 0.7 ± 0.2 ... ... ... ...
| 4–2 S(2)     | 1.284             | 0.6 ± 0.2 ... ... ... ...
| 2–0 Q(7)     | 1.287             | 1.9 ± 0.2 ... ... ... ...
| 2–0 Q(8)     | 1.302             | 0.7 ± 0.2 ... ... ... ...
| 4–2 S(1)     | 1.311             | 0.9 ± 0.2 ... ... ... ...
| 5–3 S(5)     | 1.312             | 0.7 ± 0.2 ... ... ... ...
| 3–1 Q(1)     | 1.314             | 1.2 ± 0.2 ... ... ... ...
| 3–1 Q(2)+2–0 Q(9) | 1.318+1.319 | ... 1.6 ± 0.2 ... ... ...
| 3–1 Q(3)     | 1.324             | 1.3 ± 0.2 ... ... ... ...
| 3–1 Q(4)     | 1.333             | 0.5 ± 0.2: ... ... ...
| 2–0 O(3)     | 1.335             | 2.7 ± 0.2 ... ... ... ...
| 3–1 Q(5)+4–2 S(0) | 1.342+1.342 | ... 1.6 ± 0.2 ... ... ...
| 5–3 S(3)     | 1.347             | 0.7 ± 0.2 ... ... ... ...
| 3–1 O(3)+4–2 Q(4) | 1.418       | ... 1.3 ± 0.4 ... ... ...
| 4–1 Q(5)+2–0 O(5) | 1.430+1.432 | ... 2.1 ± 0.4 ... ... ...
| 2–0 O(6)     | 1.487             | 1.0 ± 0.4: ... ... ...
| 3–1 Q(13)    | 1.502             | 0.6 ± 0.3: ... ... ...
| 3–1 O(5)     | 1.522             | 1.3 ± 0.4 ... ... ... ...
| 2–0 O(7)     | 1.545             | 0.7 ± 0.3: ... ... ...
| 4–2 O(5)     | 1.622             | 0.9 ± 0.3 ... ... ... ...
| 3–1 Q(7)     | 1.645             | 0.7 ± 0.2 ... ... ... ...
| 1–0 S(11)    | 1.650             | 1.0 ± 0.3 ... ... ... ...
| 1–0 S(10)    | 1.666             | 1.1 ± 0.3 ... ... ... ...
| 1–0 S(9)     | 1.688             | 1.9 ± 0.4 2.1 ± 0.3 7.4 ± 0.3 ... 0.9 ± 0.3 0.7 ± 0.3: ...
| 1–0 S(8)     | 1.715             | 1.4 ± 0.4 1.2 ± 0.2 5.2 ± 0.3 ... 0.7 ± 0.3: 0.7 ± 0.3: ...
| 1–0 S(7)     | 1.748             | 12.1 ± 0.4 7.5 ± 0.2 33.7 ± 0.3 1.9 ± 0.2 3.8 ± 0.3 2.5 ± 0.3 ...
| 1–0 S(6)     | 1.788             | 7.9 ± 0.4 5.0 ± 0.2 22.8 ± 0.3 1.4 ± 0.2 2.4 ± 0.3 1.5 ± 0.4 ...
| 2–1 S(9)     | 1.790             | ... 1.0 ± 0.5: ... ... ...
| 2–1 S(8)     | 1.818             | ... 1.0 ± 0.5: ... ... ...
| 1–0 S(5)     | 1.836             | 54 ± 5 31 ± 5 125 ± 5 ... ... ...
| 2–1 S(7)     | 1.853             | ... 8.0 ± 5: ... ... ...
| 1–0 S(4)     | 1.891             | 28 ± 5 16 ± 5 66 ± 5 ... ... ...
| 2–1 S(7)     | 1.945             | ... 1.969 ... ... ...

Table 2. Observed lines in the IRAS 20126+4104 outflow: knots A, B, C, X, jet-1, jet-4.
Table 2. continued.

<table>
<thead>
<tr>
<th>Term</th>
<th>H$_2$ lines</th>
<th>$\lambda$(m)</th>
<th>$F_\pm\Delta F$(10$^{-15}$ erg cm$^{-2}$ s$^{-1}$)</th>
<th>knot 1-jet</th>
<th>knot 4-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.0 ±3 :</td>
<td></td>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–0 S(3)</td>
<td>1.958</td>
<td>24 ±2</td>
<td>51 ±5</td>
<td>110 ±5</td>
<td>13 ±4</td>
</tr>
<tr>
<td>3–2 (S7)</td>
<td>1.7 ±0.8</td>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2–1 S(4)</td>
<td>2.004</td>
<td>...</td>
<td>1.3 ±0.4</td>
<td>8.3 ±0.8</td>
<td>0.6 ±0.3</td>
</tr>
<tr>
<td>3–2 S(6)</td>
<td>2.013</td>
<td>...</td>
<td>1.2 ±0.5</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1–0 S(2)</td>
<td>2.034</td>
<td>38.9 ±0.5</td>
<td>21.1 ±0.4</td>
<td>83.4 ±0.5</td>
<td>4.2 ±0.4</td>
</tr>
<tr>
<td>3–2 S(5)</td>
<td>2.066</td>
<td>0.9 ±0.3</td>
<td>0.7 ±0.3</td>
<td>2.9 ±0.4</td>
<td>...</td>
</tr>
<tr>
<td>2–1 S(3)</td>
<td>2.073</td>
<td>7.4 ±0.4</td>
<td>4.8 ±0.3</td>
<td>24.4 ±0.4</td>
<td>1.4 ±0.4</td>
</tr>
<tr>
<td>1–0 S(1)</td>
<td>2.122</td>
<td>121 ±0.4</td>
<td>66.4 ±0.4</td>
<td>246 ±0.4</td>
<td>11.1 ±0.4</td>
</tr>
<tr>
<td>2–1 S(2)</td>
<td>2.154</td>
<td>3.7 ±0.4</td>
<td>2.2 ±0.4</td>
<td>8.4 ±0.4</td>
<td>0.5 ±0.2</td>
</tr>
<tr>
<td>3–2 S(5)</td>
<td>2.201</td>
<td>1.6 ±0.4</td>
<td>0.8 ±0.3</td>
<td>4.3 ±0.4</td>
<td>0.4 ±0.1</td>
</tr>
<tr>
<td>1–0 S(0)</td>
<td>2.223</td>
<td>30.1 ±0.4</td>
<td>15.6 ±0.4</td>
<td>59.5 ±0.4</td>
<td>2.8 ±0.3</td>
</tr>
<tr>
<td>2–1 S(1)</td>
<td>2.248</td>
<td>10.9 ±0.4</td>
<td>5.5 ±0.4</td>
<td>23.0 ±0.4</td>
<td>1.6 ±0.4</td>
</tr>
<tr>
<td>3–2 S(2)</td>
<td>2.286</td>
<td>0.9 ±0.4</td>
<td>...</td>
<td>1.5 ±0.4</td>
<td>...</td>
</tr>
<tr>
<td>2–2 S(0)</td>
<td>2.355</td>
<td>2.7 ±0.5</td>
<td>1.7 ±0.5</td>
<td>5.1 ±0.5</td>
<td>...</td>
</tr>
<tr>
<td>3–2 S(1)</td>
<td>2.386</td>
<td>1.0 ±0.5</td>
<td>...</td>
<td>4.0 ±0.5</td>
<td>...</td>
</tr>
<tr>
<td>1–0 Q(1)</td>
<td>2.407</td>
<td>135 ±5</td>
<td>66 ±5</td>
<td>234 ±5</td>
<td>11 ±3</td>
</tr>
<tr>
<td>1–0 Q(2)</td>
<td>2.413</td>
<td>50 ±5</td>
<td>25 ±5</td>
<td>89 ±5</td>
<td>...</td>
</tr>
<tr>
<td>1–0 Q(3)</td>
<td>2.424</td>
<td>123 ±5</td>
<td>57 ±5</td>
<td>218 ±5</td>
<td>11 ±3</td>
</tr>
<tr>
<td>1–0 Q(4)</td>
<td>2.437</td>
<td>35 ±5</td>
<td>18 ±5</td>
<td>70 ±5</td>
<td>...</td>
</tr>
<tr>
<td>1–0 Q(5)</td>
<td>2.455</td>
<td>39 ±5</td>
<td>27 ±5</td>
<td>142 ±5</td>
<td>...</td>
</tr>
</tbody>
</table>

[Fe II] lines

| $a^2$D$_{17/2}$ → $a^2$F$_{17/2}$ | 1.257 | ... | 0.6 ±0.3 | ... | 1.2 ±0.3 |
| $a^2$D$_{17/2}$ → $b^2$F$_{17/2}$ | 1.321 | ... | ... | 0.6 ±0.3 | ... |
| $a^2$D$_{17/2}$ → $a^2$F$_{17/2}$ | 1.644 | ... | 1.7 ±0.2 | ... | 2.0 ±0.2 |
| $a^2$D$_{17/2}$ → $a^2$F$_{17/2}$ | 1.810–1.811 | ... | 1.2 ±0.4 | ... | 1.5 ±0.4 |

Notes: 3$\sigma$ upper limits (in knot C) for the [CI] doublet (at 0.983–5 $\mu$m) and for the Br y line are 10$^{-15}$ and 6 $\times$ 10$^{-16}$ erg cm$^{-2}$ s$^{-1}$, respectively.

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**IRAS20126+4104 Knot C**

![Figure 4](image-url) Fig. 4. The 0.9–2.5 $\mu$m low-resolution spectrum of knot C in the IRAS 20126+4104 jet. An asterisk near the line identification marks the detections between 2 and 3 sigma. Telluric lines are indicated by the symbol “*$\otimes$”.
the ratios are among the following groups of transitions: 1–0S(i),1–0Q(i)+2; 2–0S(i),2–0Q(i)+2,2–0O(i)+4,2–1S(i); 3–1S(i),3–1Q(i)+2,3–1O(i)+4; with \(i = 0, 1, 2, \ldots\). The best fit was obtained excluding the 1–0S(i)/1–0Q(i)+2 pairs, which deviated more than 3σ from the average value. The final value is \(A_1 = 7.6 \pm 0.2\), and it has a very small error. For the other knots, the \(A_i\) ranges from 6 to 10 mag, with errors between 1 and 3 mag (see Table 5, Col. 3). For these knots, a few pairs of lines were available making the errors larger. With the exception of knot C, all the lines in our ro-vibrational diagrams are well-fitted by a single straight line (see Fig. 9), indicating a uniform temperature of the gas. The observed temperatures range from 2000 to 2500 K.

On the other hand, the different H\(_2\) lines detected in knot C cannot be fitted by a single line. The ro-vibrational diagram exhibits a typical curvature indicating the presence of a stratification in the gas temperature. A more elaborate model of a mixture of gas at two different temperatures can describe these data (see e.g. Giannini et al. 2002; Caratti o Garatti et al. 2006; Gredel 2007). The population densities of the lines coming from levels with an excitation energy up to ~12000 K are consistent with an excitation temperature of 2050 K. These lines indeed trace the warm component of the gas. Conversely, lines with a higher excitation energy (>12000 K) are thermalised at a higher temperature of ~5200 K. These lines trace the hot component of the gas. A single fit through all the lines only gives a measure of the “averaged” temperature (~3300 K) (see Fig. 9, top left panel). In our model the hot component is a fraction of the gas of about 8%.

Another important parameter that derives from ro-vibrational diagrams is the column density of the gas. The column densities of the warm H\(_2\) component are reported in Table 5. They are very similar to those measured in other high-mass protostellar jets (10\(^{18}\)–10\(^{19}\) cm\(^{-2}\)) (see e.g. Davis et al. 2004; Gredel 2006), and they are 1–2 orders of magnitude higher than the values observed in low-mass jets.

Finally, from the analysis of Fig. 9, it is worth noting that the H\(_2\) gas along the flow is fully thermalised. That we detect no lines with \(v \geq 6\) indicates that fluorescence mechanisms do not play an important role in the excitation (see e.g. Black & van Dishoeck 1987). Excitation by non-thermal processes like fluorescence in the presence of a UV field would cause the vibrational temperature to be different from the rotational temperatures, and thus lines belonging to different vibrational series should not be located on the same line (see e.g. Hora & Latter 1994). As a consequence, we should observe strong deviations from the smooth (or linear) Boltzmann distribution of our ro-vibrational diagrams (see also Gredel 2007). Apparently, this contrasts with results of Sect. 3.2.2, where the presence of a PDR was inferred. Such a PDR could produce enough far-UV radiation to excite the higher vibrational levels of the H\(_2\) and induce a fluorescent emission (see e.g. Burton 1992), which we do not detect. To evaluate a possible contribution of the PDR...
to the observed lines, we used the “PDR toolbox”\textsuperscript{3}. The observed [C II] 158 \textmu m diffuse line intensity (considering an LWS beam-width of 80′′) is \(\sim 2.5 \times 10^{-2} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}\). Assuming that all the emission arises from the PDR and that the density is \(10^5-10^6 \text{ cm}^{-3}\) (Cesaroni et al. 1999), we obtain a relatively faint FUV flux of \(G_0\) between 10 and 100 (where \(G_0\) is measured in units of \(1.6 \times 10^{-3} \text{ erg s}^{-1} \text{ cm}^{-2}\)). Under these circumstances the PDR surface temperature does not exceed 100 K (Kaufman et al. 1999) and the contribution to the overall H\textsubscript{2} emission is negligible. For example, the diffuse line intensity of the 0–0 S(1) is \(10^{-6}-10^{-5} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}\), while we obtain \(\sim 6 \times 10^{-5} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}\) from our observations (dividing by the ISO-SWS FoV). In the NIR the emission from the shock (at 2.12 \textmu m) is four orders of magnitude greater. These results clearly indicate that the detected H\textsubscript{2} arises mostly from shocks.

### 3.4.2. The cold H\textsubscript{2} component from MIR lines

As a second step in our analysis, we also used the ISO-SWS lines to study the cold component of the gas, which is usually traced by lines with excitation energy lower than 5000 K, namely the 0–0 S lines (with \(J_{\text{fin}} \leq 5\)) between 6 and 28 \textmu m in the ISO-SWS spectrum.

Since we do not know the spatial extent of the emitting region, we matched the column densities of the 1–0 Q lines present in both NICS and SWS spectra, to intercalibrate the data in the ro-vibrational diagram. Indeed the measured ISO-SWS fluxes of the 1–0 Q lines are very close to those measured in knot C. Therefore we have assumed that its column density is representative of the warm H\textsubscript{2} component detected with ISO, as well. The result is shown in Fig. 10. The SWS lines coming from the 0 and 1 levels are overplotted on the ro-vibrational diagram of knot C (shown in Fig. 9, top left panel). Although there is some scatter among the 1 data points (two 1–0 Q and 1–0 O lines have slightly higher and lower column densities, respectively), the overall fit is quite satisfactory. In particular, the 0–0 S lines reveal the presence of a cold gas component at about 520 K, which has a higher column density than the other components (\(N_{\text{H}_2} \sim 9.7 \times 10^{21} \text{ cm}^{-2}\), see also Fig. 10).

To reproduce the observed ro-vibrational diagram, we calculated a theoretical H\textsubscript{2} spectrum for a mixture of three H\textsubscript{2} layers in LTE condition at a temperature of 520, 2050, and 5200 K. The adopted LTE code (see also Caratti o Garatti et al. 2006) computes the line intensities involving levels with \(0 \leq v \leq 14\) and \(0 \leq J \leq 29\) (\(E_J \leq 500000\) K). Ro-vibrational energies were taken from Dabrowsy (1984) and the Einstein coefficients from Wolniewicz et al. (1998). We assumed an ortho/para ratio equal to three (as also evinced from our ro-vibrational diagrams). The resulting model is plotted in Fig. 10, and properly fits our observations. In this case the warm and hot components are only a small fraction of the total H\textsubscript{2} gas, i.e. less than 1%.

### 3.4.3. H\textsubscript{2} luminosity

In the last step of our analysis, we inferred \(L_{\text{H}_2}\). Once the physical parameters \((A_V, T)\) for each knot were derived, we reddened the 2.12 \textmu m flux obtained from the imaging (see Table 5, Col. 5), adopting the Rieke & Lebofsky (1985) reddening law, and computed the line ratios with the other H\textsubscript{2} lines by applying our radiative LTE code at \(T = T_{\text{avg}}\). From these ratios, the absolute intensities of individual lines were computed and the H\textsubscript{2} luminosity of each knot was derived (see Table 5, Col. 6). The sum of these values gives a total \(L_{\text{H}_2}\) of the flow of \(4.6 \pm 0.3 L_{\odot}\).

An average temperature reproduces the contribution of both the warm and hot gas components to the radiated energy in H\textsubscript{2} well (see Caratti o Garatti et al. 2006). We are not taking the luminosity of the “cold” component into account, which, however,

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\textsuperscript{3} The “PDR Toolbox” is available at \url{http://dustem.astro.umd.edu} and contains downloadable FIR line diagnostic information about PDRs. The tool has been created by Mundy, Wolfire, Lord, and Pound, and it is based on the new PDR models of Kaufman et al. (1999).
Fig. 7. Left $P-V$ diagram for slit 3. On the left panel the H$_2$ (TNG) image indicates the position of the slit and knots. Y offsets are displayed from the position of the star in the centre of the image. The contour levels are 3, 6, 12, 20, 30, $50 \times \sigma$. On the right, the uncalibrated H$_2$ (2.12 $\mu$m) spectrum from CGS4 is reported. The contour levels are 3, 5, 7, 10, $13 \times \sigma$. Right $P-V$ diagram for slit 4. Y offsets are displayed from the position of knot D. The image contour levels are 3, 6, 30, 50, 100, 130, 210, 235, 300, $420 \times \sigma$. The levels of the spectra are 3, 5, 7, 10, $13 \times \sigma$.

here can be considerable due to the extremely high column density of the gas. In order to evaluate this, we assumed that the measured SWS flux from the 0–0 $S$ lines is the total flux emitted by the shocked cold H$_2$ gas of the flow and that the contribution of non-thermal emission is negligible, as seen in Sect. 3.4.1. We then computed the luminosity of an LTE gas at $T = 520$ K, using the 0–0 $S(1)$ observed dereddened intensity to derive the absolute intensities of the remaining lines. The luminosity of the “cold” gas is $3.6 \pm 0.6 L_\odot$. Added to the previous estimate, this gives a total $L_{H_2}$ for the entire flow of $8.2 \pm 0.7 L_\odot$.

3.5. Mass flux, mass, and energy of the H$_2$ jet

The physical and kinematical parameters inferred in the previous sections allow us to evaluate important kinematical and dynamical properties of the flow. Therefore, we estimated the mass flux rate of the flow ($\dot{M}_{\text{out}}$) from the H$_2$ in order to compare it with the mass outflow rate and the mass accretion rate of the protostar previously obtained from CO observations and models (see e.g. Shepherd et al. 2000; Cesaroni et al. 2005; Lebrón et al. 2006). The value of $\dot{M}_{\text{out}}$(H$_2$) can be written as $\dot{M}_{\text{out}} = 2 \mu m_H N_{H_2} A v_t / \ell_t$, where $\mu$ is the average atomic weight, $m_H$ the proton mass, $N_{H_2}$ the H$_2$ column density, $A$ the area of the H$_2$ knot, $v_t$ the tangential velocity, and $\ell_t$ the projected length of the knot (see e.g. Nisini et al. 2005; Podio et al. 2006; Antoniucci et al. 2007).

Using the 2.12 $\mu$m column density of Table 5, the radial velocities of Table 4, and assuming an average inclination for all the knots of 20$^\circ$ with respect to the plane of the sky, we estimate mass fluxes between $10^{-6}$ and $10^{-8} M_\odot$ yr$^{-1}$ (see Table 5, Col. 7). In fact, these values represent lower limits. From the ro-vibrational analysis, the cold gas column density is two orders of magnitude higher than the warm component (e.g. 0–0 $S$ lines have a column density $N_{H_2} \sim 9.7 \times 10^{21}$ cm$^{-2}$). Using this value, and assuming the same velocity and extension of the emitting area of the 2.12 $\mu$m line, we obtain $\dot{M}_{\text{out}}$(H$_2$) $\sim 7.5 \times 10^{-4} M_\odot$ yr$^{-1}$.

Fig. 8. Line profiles of the knots in the 1-0 $S(1)$ line of H$_2$ at 2.12 $\mu$m.
It is worth noting, however, that this value should only be considered as an estimate of the mass flux, for two reasons. Firstly, we have set \( l_e \) and \( v_i \) as equal for both H\(_2\) components. Probably, such an estimate is a lower limit, since \( l_e/\nu_i \) is the cooling time \( t_c \) of the shock. In this case, the kinematically determined \( t_c \) of knot C is \( 1.9 \times 10^{10} \) s. Also other methods have been used in the literature to derive \( t_c \). Davis et al. (2000) adopt the approximation \( t_c \sim 3 \times 10^6 n_e^{-1} T_3^{-2} \) (in seconds), where \( n_e \) is the density in units 10\(^6\) cm\(^{-3}\) and \( T_3 \) the temperature in units of 1000K (Smith & Brand 1990). In this way, adopting \( n_{H_2} = 10^8 \) cm\(^{-3}\) (Cesaroni et al. 1999) and two different temperatures, for knot C, we would obtain \( t_c \) (warm) = \( 6.1 \times 10^8 \) s (with \( T = 20000 \)K), and \( t_c \) (cold) = \( 1.5 \times 10^8 \) s (with \( T = 500 \)K). The \( M_{\text{out}} \) of the cold component would then be remarkably similar to the previous estimate. Moreover, it is very close to the mass outflow rates derived by Shepherd et al. (2000) and Lebrón et al. (2006) from the CO mm analysis (\( 8.1 \times 10^{-4} \ M_\odot \ yr^{-1} \), and \( 3.4 \times 10^{-3} \ M_\odot \ yr^{-1} \), respectively).

In addition, we can derive another estimate of the mass flux from the luminosity of the [O I] line (at 63 \( \mu \)m) using the approximate formula \( M_{\text{out}} \sim 10^{-4} \times (L(63 \mu \text{m})/L_\odot) \ M_\odot \ yr^{-1} \) (see e.g. Hollenbach & McKee 1989; Liseau et al. 1997; Cabrit 2002). As a result, we get \( M_{\text{out}}(\text{OI}) = 2 \times 10^{-4} \ M_\odot \ yr^{-1} \). Such an estimate is an upper limit, however, since part or all of the [O I] emission could originate from the PDR.

To derive the mass of each knot, we assumed \( M_k = 2 \mu m_{\text{H}} n_{\text{H}_2} A_k \). For knot D, where \( n_{\text{H}_2} \) was not measured, we assumed an average value of 4.4 \( \times 10^{18} \) cm\(^{-2}\) from Table 4. The total mass \( (\sum_k M_k) \) of the warm gas is \( \sim 10^{-2} \ M_\odot \). Assuming an average value for the inclination of the flow of 20\(^\circ\), the dynamical timescale of the flow \( (\tau_d) \) is \( \sim 1.3 \times 10^4 \) yr, the total momentum \( P(\tau_d) \) is 0.06 \( M_\odot \) km s\(^{-1}\), the kinetic energy \( E_k(\tau_d) \) is \( 5 \times 10^{43} \) erg, and the momentum flux \( P/\tau_d \) is \( 5 \times 10^{-6} \ M_\odot \) yr\(^{-1}\) km s\(^{-1}\). We note that these values must be considered as lower limits, since the mass of observable shocked warm H\(_2\) is only a small fraction of the total shocked molecular hydrogen mass, as seen previously. If we compute these quantities by taking the column density of the cold component of

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**Fig. 9.** Rotational diagram of knots in the IRAS 20126+4104 jet obtained from the low-resolution NIR spectroscopy. Different symbols indicate lines coming from different vibrational levels, as coded in the upper right corner of the boxes. The inferred temperature and extinction are indicated in the upper right corner of the box.
In comparison with the value of obtained a precession period of \( \sim 10^5 \) cm, we would obtain \( n_{\text{H}_2} \sim 2 \times 10^4 \) cm\(^{-3} \), as in Cesaroni et al. (1999).

This could indicate that the origin of the two observed 'precessions' is different or that the precession period changed over time. The long-period precession was interpreted by Shepherd et al. (2000) and Cesaroni et al. (2005) as caused by the interaction between the disc of IRAS 20126+4104 and a stellar companion of a few solar masses. However, it is unlikely that the small-period precession we observe is caused by the orbital motion of the jet source around its companion. Since the orbital radius is given by the following equation (see Anglada et al. 2007)

\[
r = \frac{\text{tan}(\phi/2) \lambda_\text{H_2}}{\text{sin}(\delta)},
\]

the result is that \( r \sim 400 \) AU. The radius of IRAS 20126+4104 disc was estimated around 800 AU (Cesaroni et al. 1997), meaning that the companion would intersect the disc. Alternatively, the precession could have changed with time. The ejection of a third companion in a hierarchical triple system, for example, might have led to the formation of a tighter binary system and to shortening of the orbital period. However, this hypothesis does not explain the different position angles on the sky measured in the two precession modes (\(-60.9^\circ\) and \(-37.9^\circ\), respectively).

It seems more likely, then, that the complex axis-wandering is induced by tidal interactions of multiple stellar companions. Indeed IRAS 20126+4104 is not a single compact source, but is composed of a small cluster of YSOs (De Buizer 2007); therefore, the dynamics of such a system can be extremely complicated. It is indeed beyond of the scope of this paper to obtain a rigorous modelling for the dynamics of such a system.

4.2. \( \text{H}_2 \) jet vs. CO outflow

Observations of protostellar jets in low-mass YSOs support the idea that their molecular outflows are driven and accelerated by the highly-collimated bipolar jets. Outflows from intermediate- and high-mass sources, on the other hand, are often poorly collimated, and only in a few cases is there clear evidence of a driving jet. This has often led to the suggestion that these outflows could be driven by a different mechanism, such as, a wide-angle radial wind (see e.g. Arce et al. 2007).
Table 5. Physical parameters of the H\textsubscript{2} knots in IRAS 20126+4104 derived from the low-resolution spectroscopy and imaging.

<table>
<thead>
<tr>
<th>Knot</th>
<th>Average Temperature (K)</th>
<th>(A_{\text{v}}(\text{H}_2)) (mag)</th>
<th>(N_\text{H}_2) (10\textsuperscript{16} cm\textsuperscript{-2})</th>
<th>Flux (2.12 \mu m) (10\textsuperscript{-14} erg cm\textsuperscript{-2} s\textsuperscript{-1})</th>
<th>(L_\odot^a) ((L_\odot))</th>
<th>(M_{\text{dot}}(\text{H}_2)^b) (10\textsuperscript{8} M\odot yr\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2120 ± 70</td>
<td>10 ± 3</td>
<td>5.4</td>
<td>29.9 ± 0.2</td>
<td>0.70 ± 0.13</td>
<td>18</td>
</tr>
<tr>
<td>B</td>
<td>2020 ± 60</td>
<td>6 ± 1\textsuperscript{c}</td>
<td>3.6</td>
<td>10.9 ± 0.1</td>
<td>0.21 ± 0.03</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>3300 ± 100</td>
<td>7.6 ± 0.2</td>
<td>12.5</td>
<td>71.5 ± 0.3</td>
<td>3.12 ± 0.24</td>
<td>192</td>
</tr>
<tr>
<td>D</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>6.4 ± 0.1</td>
<td>0.12\textsuperscript{d}</td>
<td>...</td>
</tr>
<tr>
<td>jet - knot 1</td>
<td>2380 ± 90</td>
<td>6 ± 3</td>
<td>1.7</td>
<td>2.4 ± 0.1\textsuperscript{e}</td>
<td>0.06 ± 0.01</td>
<td>2</td>
</tr>
<tr>
<td>jet - knot 2</td>
<td>2350 ± 70</td>
<td>6 ± 3</td>
<td>1.7</td>
<td>0.1 ± 0.0</td>
<td>0.02\textsuperscript{d}</td>
<td>...</td>
</tr>
<tr>
<td>jet - knot 3</td>
<td>2350 ± 70</td>
<td>6 ± 3</td>
<td>1.7</td>
<td>2.7 ± 0.5</td>
<td>0.04\textsuperscript{f}</td>
<td>...</td>
</tr>
<tr>
<td>jet - knot 4</td>
<td>2020 ± 70</td>
<td>6 ± 3</td>
<td>1.7</td>
<td>10.0 ± 0.2</td>
<td>0.2 ± 0.1</td>
<td>8</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Derived from the average temperature. The contribution from the cold component of the gas is not taken into account. The \(L_\odot\), from the cold component, as measured from the 0–0 S lines of the ISO spectrum, is \(L_\text{cold} = 3.6 ± 0.4 L_\odot\); \textsuperscript{b} derived from the average temperature. The total \(N_\text{H}_2\) column density is measured by comparing the intrinsic (per unit mass) and observed flux of the 1–0 S(1) (2.12 \mu m) line; \textsuperscript{c} \(A_v\) measured from the [Fe\textsc{ii}] lines (1.64 and 1.26 \mu m) is 11 ± 7 mag; \textsuperscript{d} Computed assuming \(T_\text{ex} = 2000\) K and \(A_v = 6\) mag; \textsuperscript{e} \(A_v\) measured from the [Fe\textsc{ii}] lines (1.64 and 1.26 \mu m) is 7 ± 4 mag; \textsuperscript{f} Flux([Fe\textsc{ii}]) = 3 ± 10\textsuperscript{-15} erg cm\textsuperscript{-2} s\textsuperscript{-1}; \textsuperscript{g} Computed assuming \(T_\text{ex} = 2350\) K and \(A_v = 6\) mag; \textsuperscript{h} Computed assuming \(T_\text{ex} = 2020\) K and \(A_v = 6\) mag.

Table 6. Comparison between H\textsubscript{2} jet and CO outflow physical properties of the IRAS 20126+4104 flow.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(H_2)</th>
<th>CO\textsuperscript{a}</th>
<th>CO\textsuperscript{b}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (M\odot)</td>
<td>0.6</td>
<td>53</td>
<td>16.3</td>
</tr>
<tr>
<td>(v\text{rot}) (km s\textsuperscript{-1})</td>
<td>(–8, 47)</td>
<td>...</td>
<td>(4, 55)</td>
</tr>
<tr>
<td>(v\text{blue}) (km s\textsuperscript{-1})</td>
<td>(–14, –42)</td>
<td>...</td>
<td>(–11, –58)</td>
</tr>
<tr>
<td>(\tau_0) (10\textsuperscript{4} yr)</td>
<td>1.3</td>
<td>6.4</td>
<td>...</td>
</tr>
<tr>
<td>(M) (10\textsuperscript{3} M\odot yr\textsuperscript{-1})</td>
<td>0.75</td>
<td>0.81</td>
<td>3.4</td>
</tr>
<tr>
<td>(E\text{dot}) (10\textsuperscript{45} ergs)</td>
<td>4</td>
<td>5</td>
<td>130</td>
</tr>
<tr>
<td>(P) (M\odot km s\textsuperscript{-1})</td>
<td>50</td>
<td>403</td>
<td>1490</td>
</tr>
<tr>
<td>(P) (10\textsuperscript{-3} M\odot yr\textsuperscript{-1} km s\textsuperscript{-1})</td>
<td>4</td>
<td>6</td>
<td>310</td>
</tr>
</tbody>
</table>

\textsuperscript{a} From Shepherd et al. (2000). \textsuperscript{b} From Lebrón et al. (2006).

Apparent IRAS 20126+4104 represents a particular example of poorly collimated outflow powered by a protostellar jet. The poor collimation of this outflow has been explained by the severe precession of the jet. It is thus interesting to investigate whether the properties of the IRAS 20126+4104 H\textsubscript{2} jet meet the physical parameters of the CO outflow, i.e. if the jet is powerful enough to accelerate the surrounding medium and drive the outflow. This is indeed a fundamental question, because the YSO accretion rate is often estimated from the mass flux rate of IRAS 20126+4104 inferred by Cesaroni et al. (2005) (2 \times 10\textsuperscript{-3} M\odot yr\textsuperscript{-1}), and this is quite unlikely. This discrepancy could be then explained by the presence of (undetected) multiple jets (winds) driven by other YSOs near the source that would substantially contribute to power the CO outflow.

4.3. Shock conditions along the jet

As the previous results point out, the cold H\textsubscript{2} component of the jet plays a major role in the kinematics and dynamics of this outflow. It is therefore desirable to discuss the origin of this component in more detail.

A prevalence of C-type shocks along the flow could explain our findings. Indeed C-type shocks produce a high column density in the 0–0 lines (see e.g. Flower et al. 2003; McCooey et al., 2004), which are very sensitive to these shocks. The column densities in our 0–0 lines could not be explained by a J-type shock (see e.g. Le Bourlot et al. 2002). Except for the [Fe\textsc{ii}] and the [O\textsc{i}] emission close to the source, the emission observed along the flow only comes from the H\textsubscript{2}. Only the inner region near the source position exhibits hints of ionic emission. There is no evidence of the ionised jet detected in the radio by Hofner et al. (2007), probably confined to a region very close to the source and highly extinguished. On the other hand, the complete absence of any ionic emission in the other knots of the flow should not be attributable to a high extinction value, since the measured \(A_v\) values along the jet are relatively low. Such a behaviour has already been observed in several low-mass protostellar jets. They usually show only H\textsubscript{2} emission, or, at most, a hint of ionic emission close to the exciting source (see e.g. Giannini et al. 2004; Caratti o Garatti et al. 2006). It is also clearly observed in the high-mass IRAS 18151-1208 jet.
accretion rates (see e.g., Smith 2002; Froebrich et al. 2003). Consequently, it has been shown for low-mass YSOs that the total H$_2$ luminosity of the jets is proportional to their mechanism. Recently, it was argued that a tight correlation between the velocity of the jet and the H$_2$ luminosity of the object and implies that $M_{\text{acc}}$ increases with the luminosity (i.e. mass) of the protostar. In Fig. 12, we report the results obtained from the sample of Caratti o Garatti et al. (2006). The diagram compares the measured outflow H$_2$ luminosity versus the bolometric source luminosity, both on a logarithmic scale. We have included the new data from IRAS 20126+4104 (positioned in the upper right corner). The best fit previously obtained fits our object, perfectly, suggesting that the relation observed for high-mass jets also applies to more massive jets in their earliest stage of formation. According to the dynamical timescales of the outflow and the jet (a few times $10^4$ years), IRAS 20126+4104 has not yet reached the main sequence (MS) and has not yet developed any hypercompact HII (HCHII) region, which may affect the collimation of the jet/outflow system (Beuther & Shepherd 2005). Most importantly, the bolometric luminosity of the source mainly comes from accretion (see Cesaroni et al. 1999, 2005). In these works, the authors obtain for this source an accretion luminosity of $1.2 \times 10^4 L_\odot$ for a mass accretion rate of $\sim 1 - 2 \times 10^{-3} M_\odot \text{yr}^{-1}$. Moreover, that we obtain an accretion rate of $30 - 40\%$ for the accretion rate from the H$_2$ strengthens the reliability of our findings, since for high-mass sources we would expect a ratio of the mass ejection/accretion rate higher than the value ($\sim 0.1$) usually derived for the low-mass objects (see e.g. Cabrit 2007).

Finally, we compare our results with the $L_{H_2}$ of two high-mass jets previously investigated by means of NIR spectroscopy, i.e. IRAS 18151-1208 ($L_{H_2} = 0.7 L_\odot$, Davis et al. 2004) and IRAS 11101-5829 ($L_{H_2} \geq 2 L_\odot$, Gredel 2006). These sources have almost the same $L_{bol}$ as IRAS 20126+4104. The $L_{H_2}$ estimates are quite close to the H$_2$ luminosity of IRAS 20126+4104 obtained from the warm H$_2$ component (i.e. from our NIR analysis, $L_{H_2} = 4.6 \pm 0.3 L_\odot$). For comparison, the values of the IRAS 18151-1208 and IRAS 11101-5829 jets were also included as lower limits in Fig. 12. It is also worth noting that the slightly lower value found by Davis et al. (2004) could be caused by the high extinction values (10–30 mag) observed towards this flow. Indeed an MIR investigation could reveal whether the cold H$_2$ component plays a major role in the cooling of those jets, as well.

4.5. Comparing high- and low-mass jets

The three high-mass protostellar jets spectroscopically investigated up to date share similar characteristics. Like the low-mass jets, they are collimated and powerful enough to drive their outflows. The jet is formed close to the source, as we observe e.g. in IRAS 20126+4104 knot X (located $\sim 1700$ AU from the source) or in IRAS 11101-5829 knot HH136 J2 (located $\sim 3000$ AU from the source), indicating that the collimation of the jet occurs close to the source. They show molecular and ionic shocked emission

Fig. 12. $L_{H_2}$ vs. $L_{bol}$ including the IRAS 20126+4104 jet (also considering the luminosity of the cold component, the new datapoint is located in the upper-right corner of the diagram). Values for IRAS 18151-1208 and IRAS 11101-5829 jets have been included as lower limits, as well (see discussion in the text). A dashed line indicates the previous fit from Caratti o Garatti et al. (2006).
along the flow, and no evidence of fluorescent excitation. The observed jet velocities are similar to those of the CO outflow. Where the extinction is low, some jets (e.g. IRAS 11101-5829, IRAS 18162-2048) also show HH objects. Some kinematical and dynamical quantities, such as mass flux, momentum flux, luminosity, and kinetic energy, are greater, however, than in low-mass jets, because the powering YSO is more massive. Moreover, a precession-wiggling morphology is observed in most of the massive collimated H2 jets, often with large precessing angles (up to \(-40\)° in IRAS 20126+4104) (e.g. IRAS 16547-4247, Brooks et al. 2003; IRAS 18151-1208, Davis et al. 2004; IRAS 11101-5829, Gredel 2006; M17 disc silhouette, Nünberger et al. 2007; IRAS 07427-2400, IRAS 20293+3952, and IRAS 23033+5951, Nanda Kumar et al. 2002). Precession is also observed in low-mass jets, but it is neither as frequent nor as pronounced (usually the precession angles are less than \(10\)°). All this indicates that the dynamical interactions among massive stars are stronger and more frequent than in low-mass star-forming regions. Such complex dynamics could also explain the confused H2 morphology of some jets and the lack of collimation in some massive outflows. Finally, the lack of jets and the poor outflow collimation observed in several massive young sources fits the evolutionary outflow scenario proposed by Beuther & Shepherd (2005) well.

In this context, those sources that have jets detected toward them are very young (well before the MS turn-on), while those without detectable jets near the protostar have ultracompact HH (UCHII) regions. If the disappearance of a collimated jet in early B protostars stems from the presence of enhanced ionising radiation from an accreting early main sequence star, then all early B stars may be formed via accretion. In this sense, they are scaled-up versions of low-mass protostars at early phases (such as for IRAS 20126+4104, IRAS 18151-1208, IRAS 11101-5829, etc.). As YSOs evolve, developing UCHII regions that destroy the disc, the jets finally disappear, and the outflows look more like poorly collimated wind-blow bubbles (see also Arce et al. 2007).

In conclusion, the three high-mass protostellar jets spectroscopically studied appear to be scaled-up versions of the low-mass ones. Furthermore, a morphological analysis of the few intermediate- high-mass H2 jets known up to now partially supports an evolutionary jet/outflow scenario. A larger sample of intermediate- high-mass jets is, however, needed, and it would be premature to jump to the conclusion that the disc accretion-ejection paradigm can be extended to the intermediate- and high-mass protostars.

5. Conclusions

The IRAS 20126+4104 H2 jet has been extensively investigated through near-IR H2 and [Fe II] narrow-band imaging. H2 high-resolution spectroscopy, along with low-resolution spectroscopy (0.9–200 \(\mu m\)) throughout the infrared wavelength range. The kinematical, dynamical, and physical conditions of the H2 gas along the flow were probed. The main results of this work are the following:

– A high angular resolution H2 continuum-subtracted image from Subaru reveals a small-scale precession of the jet close to the source, with an angle of \((\sim 7.6)\) and a period of \(\sim 1100\) yr. This is about a factor 50 shorter than the precession period deduced from large-scale H2 images.

– H2 and [Fe II] narrow-band images show the appearance of a new knot, labelled X, roughly 1″ from the source position. No further ionic emission is detected along the flow in the narrow-band imaging, indicating that the jet is mainly molecular.

– Low-resolution spectra are rich in H2 emission, and no ionic emission is detected along the flow, with the exception of faint emission of [Fe II] close to the source position (in knots X and B). Faint [O I] and [C II] emissions are observed in the ISO-LWS spectrum. They could arise from an embedded PDR region around the source.

– The peak radial velocities of the knots range from \(-42\) to \(\sim 14\) km s\(^{-1}\) in the blue lobe and from \(-8\) to \(47\) km s\(^{-1}\) in the red lobe. Their line profiles, very broad and often with two or three velocity components, seem to indicate a bow shock structure. In both lobes, the absolute peak radial velocities of knots close to the source (A...C) are slower (0–30 km s\(^{-1}\)) than those located at greater distances (i.e. knot D, and knots 1 to 4, 40–50 km s\(^{-1}\)). This possibly confirms a change in the flow inclination angle (with respect to the sky) from \(\sim 9\)° (close to the source), to \(\sim 45\)° (in the outer knots). Assuming these inclination values, the spatial velocity of the knots is between 50 and 80 km s\(^{-1}\).

– The ro-vibrational diagrams indicate H2 excitation temperatures between 2000 and 2500 K. Stratification of temperature is detected only in knot C, which can be modelled combining a warm (\(T_{\text{ex}} = 2050\) K) and a hot (\(\sim 5200\) K) H2 component. Additionally, the ISO-SWS spectrum reveals the presence of a cold component (520 K) with a high column density.

– Furthermore, our analysis seems to indicate that the H2 is mostly excited in C-type shocks, and no evidence of fluorescent excitation has been observed.

– The estimated \(L_{\text{H2}}\) is \(8.1 \pm 0.7 L_{\odot}\), where the cold component contributes about 50% to the whole radiative cooling. The high H2 luminosity suggests that IRAS 20126+4104 has a significantly increased accretion rate compared to the low-mass YSOs. This is also supported by the measured mass flux rates from H2 lines (\(M_{\text{out}}(H_2) \sim 7.5 \times 10^{-4} M_{\odot}\) yr\(^{-1}\)) matching the previous CO estimates. Our analysis also indicates that the cold H2 component plays a major role in the kinematics and dynamics of this flow.

– Comparing the H2 and outflow parameters strongly indicates that the jet is driving the outflow, at least partially.

– By comparing the measured luminosity of the H2 jet with the source bolometric luminosity (assumed representative of the accretion luminosity), we show that IRAS 20126+4104 fits the correlation well between these two quantities already found for low-mass protostellar jets (Caratti o Garatti et al. 2006).

– Considering our results and the literature data of a few intermediate- and high-mass protostellar jets, we conclude that these few jets appear to be scaled-up versions of their low-mass protostellar counterparts.