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Letter to the Editor

# VLT-ISAAC 3–5 $\mu$m spectroscopy as a new tool for investigating $H_2$ emission in protostellar jets

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**Abstract.** We report 3–5 $\mu$m IR spectroscopy obtained with VLT-ISAAC on the IRS17 molecular hydrogen jet in the Vela-D Molecular Cloud. Together with $H_2$ emission lines from the $v = 1$ rovibrational state, the spectra show several pure rotational lines of the fundamental state with excitation temperature up to ~22 000 K. We show how theoretical rotation diagrams indicate these lines as unique both to probe the presence of collisionally excited gas in NLTE conditions and to infer the gas density.

**Key words.** stars: formation – infrared: ISM: lines – ISM: jets and outflows – ISM: individual objects: Vela clouds

## 1. Introduction

A large number of molecular jets has been so far investigated in the near infrared with the current ground-based instrumentation through large field ($\lesssim$10 arcmin) imaging and intermediate resolution spectroscopy ($R \sim 10^3$) (e.g. Eislöffel 1997). In particular, molecular hydrogen imaging of the $v = 1$–0 S(1) at 2.122 $\mu$m is extensively used for identifying knots of molecular emission, while the spectroscopy of the $H_2$ rovibrational lines lying in the 1.6–2.5 $\mu$m range is largely effective both to probe the molecular gas at thousands of Kelvin and to infer the prevailing excitation mechanism (fluorescence, C-continuos or J-ump shocks, see e.g. Black & van Dishoeck 1987; Kaufman & Neufeld 1996; Hollenbach & McKee 1989; Smith 1995). Recently, space-born spectroscopy evidenced the advantages of observing in the mid-IR the ground state $H_2$ pure rotational transitions, emitted by levels with excitation energy between 0 and ~10 000 K. These appear of particular interest because, in addition to be practically unaffected by extinction problems, they are characterized by significantly different critical densities (spanning from ~$10^3$ to $10^5$ cm$^{-3}$), which make them particurlarly suitable both to probe shock components at different temperatures (from few hundreds to thousands of Kelvin, e.g. Benedettini et al. 2000; Nisini et al. 2000) and to trace collisionally excited gas in NLTE conditions. Unfortunately, these observations are severely limited by the unavoidably poor spatial resolution. Now, VLT-ISAAC has opened a window in the thermal IR (3–5 $\mu$m) investigable with high to intermediate spectral resolution at an adequate plate scale for sampling the individual knots within the molecular jets, thus offering the opportunity to diagnose the local variations of the physical conditions by using the unique capabilities of the pure rotational $H_2$ lines.

In this paper we report one of the first observations of 3–5 $\mu$m long-slit spectroscopy of protostellar jets. Our target is the molecular hydrogen jet we have recently discovered in the Vela-D Molecular Cloud, namely the IRS 17 jet (Lorenzetti et al. 2001, hereinafter Paper V, following the numbering of previous papers on the same subject). It results composed by a large number of individual bright knots extending up to a distance of ~0.3 pc from the central driving source. Previous infrared spectroscopy in the 1.6–2.5 $\mu$m range with NTT-SOFI has revealed it is a quite rare example of *pure* molecular jet with a low excitation degree, as implied by the lack of both [Fe II] lines and $H_2$ transitions coming from levels with $v \geq 3$. For this reason such a jet appears as a well tailored candidate to search for thermal $H_2$ pure rotational lines and to investigate their relative importance with respect to rovibrational contributions. Moreover, being several bright knots quite well aligned along the jet axis, they result easily accomodable within a single slit, giving the further observative advantage to allow a multiple diagnostic along the jet in a single exposure.

## 2. Observations and results

Figure 1 shows the $H_2$ (2.122 $\mu$m) continuum subtracted image of the IRS 17 jet, which was obtained in a previous observing run with NTT-SOFI (Paper V). It results

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in about 20 knots of emission emanated from the central candidate driving source IRS17-40 ($\alpha_{1950} = 08^h44^m47^s76$; $\delta_{1950} = -43°43'35.8''$), which is marked in the figure with a cross. Out of them, six knots, labelled with the same identification as in Paper V (namely C2, C3, C5, G1, G2, G3) have been spectroscopically investigated with ISAAC (LW arm). The same knots had been observed with SOFI at low resolution ($R \sim 600$) between 1.6–2.5 $\mu$m (Paper V). In this paper the intensities of the lines lying in the SOFI domain have been used together with those derived from the ISAAC observations.

These latter were carried out in February 2001. We performed long slit spectroscopy with a medium resolution grating ($R \approx 10^3$ with a $2 \times 120$ arcsec slit) in the wavelength range 2.7–5.1 $\mu$m. The slit position angle (148°.7), has been defined on the basis of the SOFI image and fine tuned with the pre-imaging procedure at the VLT telescope. We conducted our observations by chopping and nodding the targets in different positions along the slit. The total integration time per grating position is 660 s and 2200 s between 2.7–4.0 $\mu$m and 4.4–5.1 $\mu$m, respectively. The data reduction and calibration were performed by using the IRAF package. The spectra were flat-fielded and sky subtracted, while flux calibration was obtained by observing the spectrophotometric standard star H 43125 (spectral type O9Ib), which was also used for removing atmospheric absorption features. To ensure a correct inter-calibration between the ISAAC and SOFI line fluxes, which are measured from the $H_2$ 2.122 $\mu$m image and are thus unaffected by slit aperture problems, we applied to the ISAAC derived fluxes a further correction for taking into account the signal losses outside the 2 arcsec slit. Since the size of the observed knots ranges between 5 and 10 arcsec$^2$ (see Table 5 of Paper V), the estimated correction factors result between 1 and 2. Wavelength calibration was obtained from the spectral lines of a Xenon-Argon lamp; the associated uncertainty is comparable with the spectral resolution element (2 pixels ≈ 5 Å). No significant shift of the line centres from the rest wavelength has been detected.

As an example of our observations we show in Fig. 2 portions of the spectrum of the brightest knot (G2), where several $H_2$ 0–0 lines have been detected. These represent one of the first detections of pure $H_2$ rotational lines from the Earth. In addition, the spectra show several $v = 1{-}0$ lines belonging to the O series. No other line coming from species different from $H_2$ has been detected. The observed lines along with their spectral identification and the excitation energy of the corresponding upper levels are reported in Cols. 1–3 of Table 1. The line shapes are well represented by gaussian profiles, which were fitted for computing the integrated line fluxes. These latter with the associated $1\sigma$ uncertainty, estimated by the rms fluctuations of the adjacent baseline, are reported in Cols. 4–9 of Table 1. Lines whose signal to noise ratio is between 2 and 3 are flagged. We note that the line with the highest excitation energy (i.e. the 0–0 S(15)) was detected only toward the G2 and G3 knots, which are those at the highest temperature ($T \sim 2500$ K, see Paper V).

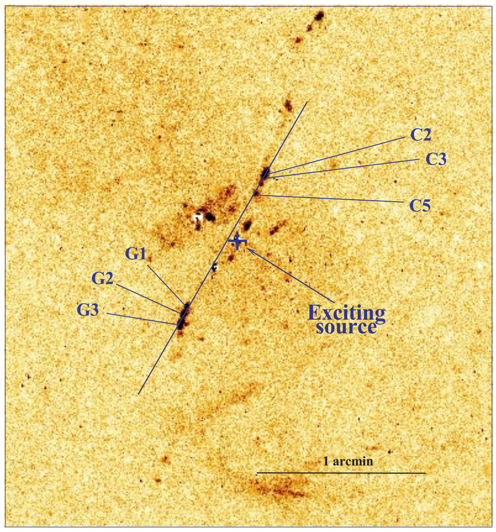


**Fig. 1.** $H_2$(2.122 $\mu$m)-K (continuum subtracted) image of the IRS17 jet. The knots spectroscopically investigated with ISAAC are labelled according to the identification code of Paper V, while the candidate exciting source (IRS17-40) is marked with a cross. The slit orientation and length are depicted as well.

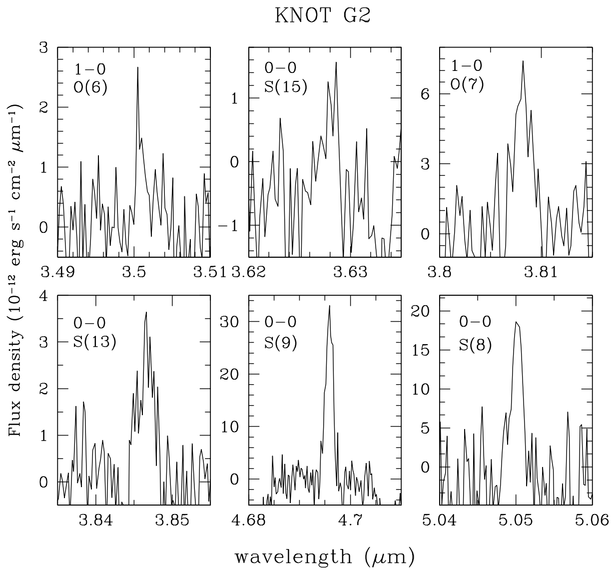


**Fig. 2.** Portions of the knot G2 spectrum where several $H_2$ 1–0 and 0–0 lines have been observed (indicated in the left upper corner of each panel).

## 3. Analysis

The line fluxes derived from our ISAAC observations have been combined with those previously derived in the 1.6–2.5 $\mu$m domain. In Paper V the SOFI fluxes were used to construct rotation diagrams from which the gas temperature and the visual extinction were simultaneously derived. These data do not show any evidence of deviation from a linear dependence, thus indicating that the traced

**Table 1.** Observed lines.

| | | | C2 | C3 | C5 | G1 | G2 | G3 |
|---|---|---|---|---|---|---|---|---|
| $\lambda_{\rm vac}$ ($\mu$m) | Transition | $E_{\rm up}$ (K) | $F \pm \Delta F$ ( $10^{-15}$ erg s$^{-1}$ cm$^{-2}$) | | | | | |
| 3.235 | 1–0 O(5) | 6950 | $8.0 \pm 1.7$ | $6.0 \pm 1.3$ | - | $7.7 \pm 1.3$ | $8 \pm 2$ | $5.4 \pm 1.0$ |
| 3.501 | 1–0 O(6) | 7583 | - | $6.5 \pm 2.1^{\dagger}$ | - | - | $8.0 \pm 1.7$ | - |
| 3.627 | 0–0 S(15) | 21 411 | - | - | - | - | $4.5 \pm 1.7^{\dagger}$ | $4.1 \pm 1.7^{\dagger}$ |
| 3.807 | 1–0 O(7) | 8364 | $4.7 \pm 1.3$ | $3.0 \pm 1.3$ | $1.7 \pm 0.5$ | - | $11.6 \pm 2.6$ | $3.6 \pm 1.0$ |
| 3.847 | 0–0 S(13) | 17 443 | $4.7 \pm 1.9^{\dagger}$ | $3.0 \pm 1.5^{\dagger}$ | $4.5 \pm 1.5$ | - | $10.8 \pm 2$ | $4 \pm 1$ |
| 3.995 | 0–0 S(12) | 15 542 | - | - | - | - | $4.5 \pm 2^{\dagger}$ | - |
| 4.577 | 1–0 O(9) | 10 340 | - | - | - | - | $12 \pm 5^{\dagger}$ | - |
| 4.695 | 0–0 S(9) | 10 262 | $28 \pm 4$ | $31.5 \pm 4.5$ | $15.1 \pm 3.7$ | $21.2 \pm 4.5$ | $100 \pm 8$ | $27 \pm 3$ |
| 5.052 | 0–0 S(8) | 8677 | - | - | - | - | $56 \pm 12$ | $7.5 \pm 3^{\dagger}$ |

Note to the Table: † refers to detections with $2 \leq S/N \leq 3$.

gas is thermalised at the derived temperature. Now, the newly detected lines offer the opportunity to check the results of Paper V and to probe possible deviations from LTE conditions. Firstly, the fluxes of the lines detected with ISAAC were corrected for the extinction by adopting the same $A_{\rm V}$ values derived from the SOFI data, which range between 8 and 18 mag. Then, from the so derived intrinsic fluxes, we calculated the data points[1] to be just superimposed onto the rotation diagrams of Paper V. An example of the obtained plots is depicted in Fig. 3, where the $H_2$ rotation diagrams relative to the G2 and C3 knots are shown. In each panel the dashed line represents the LTE best fit to the population distribution at the indicated temperature. As a general result we note that all the data points relative to the ISAAC observations do not deviate from this straight line. We will discuss in details the implications of this result in the next section. Here we point out how the ISAAC lines allow to check the accuracy on the visual extinction determination done in Paper V. Indeed, points corresponding to extinction corrected lines emitted from the same upper level are expected to be perfectly superimposed onto the rotation diagram. Such points are represented in the investigated case by the pairs of lines: 1–0 S(1) and 1–0 O(5), 1–0 S(2) and 1–0 O(6), 1–0 S(3) and 1–0 O(7) (excited at 6950, 7583 and 8364 K, respectively), which generally overlap inside the error bars in the rotation diagrams of Fig. 3. This circumstance, beside to testify that a good estimate on the $A_V$ values has been obtained, assures that a good inter-calibration exists between the SOFI and ISAAC data sets.

## 4. Discussion

We discuss here the found alignment onto a single straight line of all the observative points. Such behaviour allows to rule out excitation by non thermal processes, because in this latter case vibrational and rotational temperatures should be different, and thus lines coming from various vibrational states should lie onto straight lines with different slopes (see e.g. Hora & Latter 1994). Moreover,

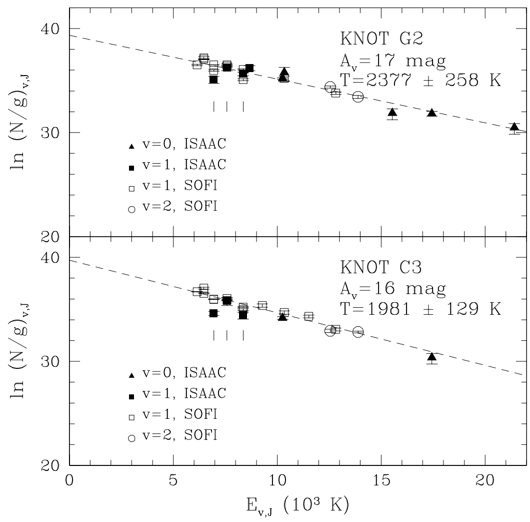


**Fig. 3.** $H_2$ rotation diagrams for the knots G2 and C3. Filled and open symbols indicate the lines observed with ISAAC and SOFI, respectively. Triangles, squares and circles distinguish transitions coming from different vibrational levels. In each panel the dashed line represents the best fit through the line fluxes observed with SOFI (Paper V) at the temperature and visual extinction indicated in the right upper corner. Vertical bars indicate the lines coming from the same upper level (see text).

the presence of multiple gas components, which should result in a smoothly curved line, rising toward higher excitation temperatures $E_{v,\rm J}$, is also rejected by our observations, which on the contrary demonstrate that the $H_2$ gas is thermalised at a single temperature up to values of $E_{v,\rm J} \sim 22\,000$ K. This finding, together with the fact that the critical densities of the involved levels span over three orders of magnitude ($10^3$–$10^6$ cm$^{-3}$), suggests to use the observed lines to infer a stringent lower limit to the gas density. To examine this possibility we developed a NLTE model for the population of the first 51 levels of $H_2$ (which correspond to a maximum excitation temperature of about $\sim$25 000 K), from which are emitted transitions up to the vibrational state $v = 3$. We adopted an abundance ratio $n({\rm H})/n({\rm H_2})= 5 \times 10^{-3}$, consistent with the predicted value in dark clouds with $A_V$ larger than 4 mag (Hollenbach et al. 1991). Radiative decay rates are taken

[1] represented by the ratio $\ln[(N_{v,\rm J})/(g_{\rm J})]$ of the natural logarithm of the column density of the upper level of each transition ($N_{v,\rm J}$), divided by the statistical weight ($g_{\rm J}$).

from Turner et al. (1977). The collisional downward rates by impact of both atomic and molecular hydrogen for each pair of levels are computed from the coefficients given by Draine et al. (1983). Upward rates are computed using the principle of detailed balance. As an example, the rotation diagrams obtained at temperature $T = 2400$ K for three different values of the gas density are reported in Fig. 4. Here is evident how the $v = 1$ and $v = 2$ lines are still not thermalised for $n = 10^6$ cm$^{-3}$, while the $v = 3$ lines reach the thermal equilibrium at densities even larger than $10^7$ cm$^{-3}$. The increasing underpopulation of levels with higher vibrational state, although with similar excitation energy, has been explained by Chang & Martin (1991) as due to the higher cross section which promotes rotational more than vibrational excitation. Evidences of collisionally excited gas in NLTE have been recognized in HH 7–11 (Everett 1997), where $H_2$ lines belonging to series from $v = 1$ to $v = 3$ have been detected. In this case, however, NLTE signatures are blended with the effects caused to the presence of different temperatures components. On the contrary, the case presented here allows a straightforward intepretation. By comparing the observative diagrams of Fig. 3 with the models of Fig. 4, and by noting that the points relative to the 0–0 lines are well aligned with those of the other transitions, we can infer a lower limit to the gas density of $10^7$ cm$^{-3}$. We remark that the $v = 3$ transitions, although in principle could be used as density indicators in analogy with the 0–0 lines, are predicted to be ~100 times weaker than the 2.12 $\mu$m line.

The presence of a single temperature gas at $n \gtrsim 10^7$ cm$^{-3}$ suggests a planar shock travelling in a medium with a high pre-shock density as the most favourable excitation mechanism (Kaufman & Neufeld 1996). In Paper V we noticed that such a mechanism could explain the SOFI observations by assuming a shock velocity larger than 30 km s$^{-1}$ and a pre-shock density $\gtrsim 10^5$ cm$^{-3}$. The lower limit to the post-shock density derived here ($>10^7$ cm$^{-3}$) indicates a shock compression factor $n_{\rm post}/n_{\rm pre} \sim 10^2$, which is compatible with this kind of shocks.

## 5. Conclusions

We have presented the VLT-ISAAC 3–5 $\mu$m spectroscopy of the IRS 17 jet in Vela-D Molecular Cloud. Along the investigated knots we observed several $H_2$ 0–0 transitions with excitation energy up to ~22 000 K. These have been used together with rovibrational lines previously observed in the H–K bands to probe the gas physical conditions. The found alignment of all the data points onto a single straight line demonstrates that the gas is thermalised at a single temperature. Comparison with NLTE models has allowed to put a lower limit to the gas density of $10^7$ cm$^{-3}$ and the capability of the thermal 0–0 lines in probing collisionally excited gas in NLTE conditions has been proved. Finally, we remark that the presented observations point out to a rare case of a pure planar shock, while usually bow morphologies are more adequate to intepret the $H_2$ data.

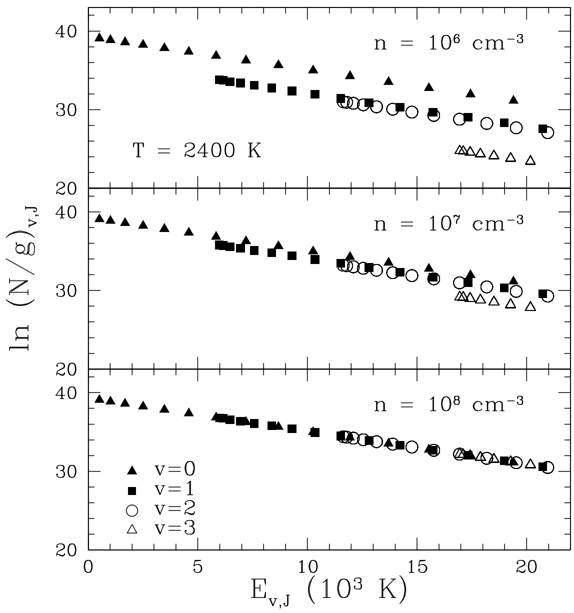


**Fig. 4.** Theoretical rotation diagrams for three density values obtained with a NLTE model for the $H_2$ excitation. Filled triangles, filled squares, open circles and open triangles refer to transitions coming from upper states with $v = 0$, 1, 2, 3 respectively. The adopted temperature is $T = 2400$ K, while the abundance ratio $n(H)/n(H_2)$ is $5 \times 10^{-3}$.

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