Spitzer spectral line mapping of the HH211 outflow

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ABSTRACT

Context. Jets from the youngest protostars are often detected only at mm wavelengths, by means of line emission of CO and SiO. However, it is not yet clear whether these jets are mostly molecular or atomic, nor whether they trace ejected gas or an entrained layer around an embedded atomic jet.

Aims. We investigate the warm gas content of the HH211 protostellar outflow to assess the jet mass-flux in the form of H₂ and investigate the existence of an embedded atomic jet.

Methods. We employ archival *Spitzer* slit-scan observations of the HH211 outflow over 5.2–37 μ m obtained with the low resolution IRS modules. Detected molecular and atomic lines are interpreted by means of emission line diagnostics and an existing grid of molecular shock models. The physical properties of the warm gas are compared with those of other molecular jet tracers and to the results of a similar study towards the L1448-C outflow.

Results. We detected and mapped the $v = 0-0$ S(0)–S(7) H₂ lines as well as fine-structure lines of S, Fe⁺, and Si⁺. The H₂ is detected to 5'' from the source and is characterized by a “cool” $T \sim 300$ K and a “warm” $T \sim 1000 \pm 300$ K component, with an extinction $A_V \sim 8$ mag. The amount of cool H₂ towards the jet agrees with that estimated from CO assuming fully molecular gas. The warm component is well fitted by C-type shocks with a low beam filling factor $\sim 0.01-0.04$ and a mass-flux similar to the cool H₂. The fine-structure line emission arises from dense gas with ionization fraction $\sim 0.5-5 \times 10^{-3}$, and is indicative of dissociative shocks. Line ratios with respect to sulfur indicate that iron and silicon are depleted relative to solar abundances by a factor $\sim 10-50$.

Conclusions. *Spitzer* spectral mapping observations reveal for the first time a cool H₂ component towards the CO jet of HH211 consistent with the CO material being fully molecular and warm at ~ 300 K. These maps detect also for the first time an embedded atomic jet in the HH211 outflow that can be traced close to the central source position. Its significant iron and silicon depletion excludes an origin from within the dust sublimation zone around the protostar. The momentum-flux seems insufficient to entrain the CO jet, although current uncertainties in jet speed and shock conditions are too large to reach a definite conclusion.

Key words. stars: formation – ISM: jets and outflows – ISM: individual objects: HH211-mm – infrared: ISM

1. Introduction

The process of mass accretion leading to the formation of low mass protostars is always associated with ejection of material in the form of well collimated high-velocity jets and/or wider slower bipolar outflows (Reipurth & Bachiller 1997; Arce et al. 2007). Accretion and ejection phenomena are believed to be intimately connected to the existence of a magnetized accretion disk around the forming protostar, but there has been no consensus so far about the exact ejection mechanism (Pudritz et al. 2007; Shang et al. 2007; Ferreira et al. 2006). The study of the physical properties of jets (e.g., temperature, density, abundances, mass flux) is therefore crucial to obtain indirect constraints on the mass accretion and ejection processes, especially in the case of protostars in the earliest evolutionary stages – the so-called Class 0 protostars – where the launching zone is heavily embedded in a dense cocoon of dust and gas.

Because of this high extinction, jets from the youngest Class 0 sources cannot be seen in the optical and are mostly traced in both near-IR H₂ and mm CO and SiO lines (Guilloteau et al. 1992; McCaughrean et al. 1994; Davis & Smith 1996).

However, it remains unclear whether the molecules trace a sheath of entrained ambient material around an unseen underlying atomic jet, or if they trace the primary jet material itself. In the latter case, the chemical composition of the jet (molecular versus atomic fraction, dust depletion) holds crucial information about the ejection zone, as the strong UV flux generated by the accretion shock should destroy dust grains and H₂ molecules in the innermost regions of the disk. A wind from these inner zones would be mostly atomic even if CO and SiO are abundant – unless the mass flux is unusually large (Ruden et al. 1990).

Mid-infrared spectroscopic observations are essential to answer these questions. A *Spitzer* study of the innermost jet regions of the Class 0 L 1448 outflow (Dionatos et al. 2009) revealed an underlying deeply embedded atomic/ionic component, not seen in the near-IR range, as well as mid-IR H₂ emission tracing the warm molecular content. Here we present a more extensive *Spitzer* mapping study of the HH211 outflow, a particularly interesting target that represents a “text-book” example of jet-driven flow.

HH211 is located in the IC 348 complex in Perseus at a distance estimated to be between 250 pc (Enoch et al. 2006),

adopted in the current paper, and ~ 320 pc (Herbig 1998; Lada et al. 2006). The driving source HH211-mm is detected in mm continuum emission (e.g. Gueth & Guilloteau 1999; Lee et al. 2007), and has been classified as a low-mass, low-luminosity Class 0 young stellar object (Froebrich 2005).

The outflow was discovered by McCaughrean et al. (1994) in near-IR H_2 emission tracing 2000 K hot, shocked gas in two bright symmetric bowshocks separated by 0.13 pc with a faint chain of knots in between. A few compact knots of atomic emission at optical and near-IR wavelengths (i.e., H_α , [SII]6730 Å and [FeII]1.64 μm) are also seen near the brightest H_2 peaks (O’Connell et al. 2005; Walawender et al. 2005, 2006; Caratti o Garatti et al. 2006). The absence of any additional shock structures on larger scales makes it the youngest outflow known so far, with a kinematical age of only 1000 yr $\times$ (V/100) km s^{-1} (Gueth & Guilloteau 1999; Eisloffel et al. 2003a).

Low velocity CO $J = 2-1$ (Gueth & Guilloteau 1999) and CO $J = 3-2$ (Lee et al. 2007) observations delineate the shape of a bipolar swept-up cavity with its ends tracing the H_2 bowshocks and its flanks connecting back to the driving source, while the high-velocity components of the same transitions reveal an inner well-collimated CO jet extending out to $\pm 25''$ from the source. The CO jet is also traced in SiO by means of interferometric observations of the $J = 1-0$ (Chandler & Richer 2001), 5–4 (Hirano et al. 2006), and 8–7 (Lee et al. 2007) transitions, and single-dish multi-transition studies (Gibb et al. 2004; Nisini et al. 2002b). Excitation of these high J levels implies that the SiO jet is warmer and denser than the outflow cavity traced by low-velocity CO emission.

All observations reveal a highly bipolar structure, with blue- and red-shifted lobes pointing southeast and northwest from the driving source. The two lobes are well separated, and both this observed morphology and the low observed radial velocities ($\sim 20 \text{ km s}^{-1}$, Gueth & Guilloteau 1999) imply that the inclination of the outflow is less than 10° from the plane of the sky (Gueth & Guilloteau 1999; Chandler & Richer 2001; Lee et al. 2007). This simple geometry is favorable to modelling. Indeed, the CO cavity shape is well fitted by a dynamical model of jet-driven bowshock propagating into a medium of decreasing density (Gueth & Guilloteau 1999). This interpretation is supported by fitting the near-IR line fluxes and morphologies at the apex of the redshifted lobe with a series of bowshocks (O’Connell et al. 2005). A *Spitzer* map obtained at the tip of the blue lobe indicates a higher excitation 40 km s^{-1} dissociative shock on that side, with a substantial UV flux (Tappe et al. 2008).

In this paper, we present archival *Spitzer*-IRS slit-scan observations covering most of the HH211 flow with low spectral resolution (Sect. 3), which we analyze to address the physical conditions and the molecular and dust content. In Sect. 4, the detected rotational H_2 transitions are employed as probes of the physical conditions in the jet close to the driving source and the shocked gas further out, and compared with an existing grid of C and J-type shock models. Atomic lines present in our spectra are treated separately as probes of a deeply embedded atomic jet, and used to measure dust depletion. Mass fluxes are inferred for the H_2 and atomic components, and compared with those measured in CO and SiO, as well as to a similar study of the inner jet of L1448. Our conclusions are presented in Sect. 5.

2. Observations and data reduction

Observations were obtained with the *Spitzer* satellite (Werner et al. 2004) and retrieved from the *Spitzer* Public Data Archive

Fig. 1. Continuum-subtracted spectrum, integrated over a region of 612 square arcseconds covering the HH211 flow (middle), shown in comparison with a spectrum of the off-outflow region of the same area (top). H_2 emission from the 0–0 S(0)–S(7) lines is detected in the outflow, together with atomic emission from the ground-state transitions of [FeII], [SiII], and [Si]. The H_2 S(0) and S(1) lines are also detected in the off-outflow spectrum, which is indicative of a diffuse line emission component not related to the HH211 flow. Diffuse emission from PAH features, such as the 11.3 μm feature, is also detected. Bottom: on-source spectrum extracted from an area equal to the LL pixel scale (110.25 square arcseconds), after removing the zodiacal light and ambient contribution presenting the intrinsic continuum emission from the outflow source.

using the Leopard software. They had been performed as part of the “Shock dissipation in nearby star forming regions” program conducted by J. Bally (P.I.). In these, the low resolution modules ($R \sim 60-130$) of the *Spitzer Infrared Spectrograph* (IRS, Houck et al. 2004) were used in slit-scan mode to cover an area of $57'' \times 73''$ and $157'' \times 168''$ for the short low (SL) and long low (LL) modules, respectively, centered on the Class 0 source HH211-mm ($\alpha_{J2000}:03\text{h}43\text{m}56.5\text{s}$, $\delta_{J2000}:+32\text{d}00\text{m}51\text{s}$). A perpendicular scan step equal to the slit width of each module was used, with a total integration time of 171 min. The combination of both IRS low resolution modules gives a complete wavelength coverage of 5.2–37.0 μm .

Initial data processing was performed at the *Spitzer* Science Center using version 15 of the processing pipeline. Spectral data-cubes were compiled using the CUBISM software package (Smith et al. 2007) and bad/rogue pixels were masked by means of visual inspection.

Figure 1 presents the extracted continuum-subtracted spectrum, integrated over a region encompassing the HH211 flow. The full series of H_2 pure rotational lines (S(0)–S(7)) were detected, along with atomic and ionic lines from the fundamental transitions of [Si], [FeII], and [SiII] at 25 μm , 26 μm , and 35 μm , respectively. For comparison, Fig. 1 also shows a spectrum of a region encompassing the same area but in a direction perpendicular to the outflow. The H_2 S(0) and S(1) lines are also detected in this off-outflow spectrum, which is indicative of a diffuse line emission component not related to the HH211 flow. Diffuse emission from PAH features, such as the 11.3 μm feature, is also

Fig. 2. $H_2 v = 0-0$ S(2)–S(7) line intensity maps of the HH211 flow observed with the *Spitzer* SL module, reconstructed with a pixel scale of $3.5''$. Contours are from $10^{-12} \text{ W cm}^{-2} \text{ sr}^{-1}$ with an increment of $8 \times 10^{-13} \text{ W cm}^{-2} \text{ sr}^{-1}$ for the para lines (even J), and from $2 \times 10^{-12} \text{ W cm}^{-2} \text{ sr}^{-1}$ with an increment of $2.5 \times 10^{-12} \text{ W cm}^{-2} \text{ sr}^{-1}$ for the ortho transitions (odd J). Crosses indicate the driving source position at $\alpha_{J2000}:03^{\text{h}}43^{\text{m}}56.5^{\text{s}}$, $\delta_{J2000}:+32^{\circ}00'51''$. In the H_2 S(5) map, points B1–B3 and R1, R2 indicate peaks of emission, where A_V and ortho to para ratio are estimated and excitation analysis is carried out.

evident. In Fig. 1, we also plot the on-source spectrum for an area equal to the LL pixel size, after subtracting the contribution of an off-source, free-of-line-emission position. This only removes zodiacal light and reveals the intrinsic mid-IR continuum from the central source, which is typical of low-luminosity Class 0 sources.

Subsequent analysis consisted of the construction of individual line emission maps, using a customized pipeline; in this, for each spatial pixel of the data-cube, the brightness of each spectral line of interest was calculated by fitting a Gaussian after subtracting a local second-order polynomial baseline. The resulting line intensity maps have a square pixel of side equal to the slit width of the IRS module, namely $3.5''$ and $10.5''$ for the SL and LL modules, respectively, while the diffraction limit of the telescope is $2.4''$ and $6.0''$ at $\lambda = 10 \mu\text{m}$ and $25 \mu\text{m}$, respectively. The astrometric accuracy of the maps was found to be good to within the limits imposed by the pixel size of each IRS module.

3. Spectral line maps

3.1. H_2 emission

Figure 2 presents the emission line maps of the S(2)–S(7) rotational H_2 lines observed with the SL–IRS modules with a $3.5''$ sampling. Contours shape a characteristic bipolar outflow pattern, where the H_2 emission is detected down to a projected angular distance $\sim 5''$ from the driving source. Further downwind, peaks of emission that can be attributed to shocked gas are observed. In the H_2 S(5) map of Fig. 2, we label these peaks as B1–B3 in the southeast, blue-shifted lobe and R1–R2 in the northwest, red-shifted lobe, respectively.

Figure 3 shows the H_2 S(5) emission map overlaid on the high-velocity CO $J = 2 \rightarrow 1$ map of Gueth & Guilloteau (1999) (upper panel) and on the SiO $J = 8 \rightarrow 7$ and CO $J = 3 \rightarrow 2$ maps of Lee et al. (2007) (lower panels). The grayscale background shows the near-IR $H_2 v = 1-0$ S(1) images from McCaughrean et al. (1994) or Hirano et al. (2006). Overall, the spatial correspondence between mid-IR and near-IR H_2 lines is quite good except towards the broadest parts of the outflow cavity, where the mid-IR emission appears to trail behind the near-IR one.

Fig. 3. (Upper panel) $H_2 v = 0-0$ S(5) map (green contours) superimposed over the high velocity CO $J = 2-1$ map of Gueth & Guilloteau (1999); (Lower panels) Inner part of the $H_2 v = 0-0$ S(5) map (green contours) superimposed on the SiO $J = 8-7$ and the CO $J = 3-2$ maps of Lee et al. (2007). The grayscale background shows the $H_2 v = 1-0$ S(1) image from McCaughrean et al. (1994) (top panel) or Hirano et al. (2006) (lower panels). The slight S-shape pattern of the S(5) emission map follows the brightness asymmetry of the cavity seen in the $2.12 \mu\text{m}$ image. In the blue-shifted jet lobe, point B1 is coincident with peak BII in CO $J = 2-1$ and BK4–6 in SiO.

In the southeastern – blue lobe, the peak of mid-IR H_2 emission closest to the source (B1) coincides with the $2.12 \mu\text{m}$ H_2 knot G in the nomenclature of McCaughrean et al. (1994), the BII knot of the CO jet (Gueth & Guilloteau 1999) and knots BK4–6 in the SiO jet (Lee et al. 2007) (see lower panel of Fig. 3). Therefore, it appears to trace mostly the jet beam. Further outwards, peak B2 is centered on a hole behind the bowshock rim delineated in the near-IR image, while peak B3 appears to lie on the bow rim (note however that the spatial extent of our SL map does not fully cover the tip of this region).

Fig. 4. Intensity maps of the HH211 flow in the $\text{H}_2\text{S}(1)$ and $\text{S}(0)$ lines (*top row*) and the atomic $[\text{SiII}]35\ \mu\text{m}$, $[\text{SI}]25\ \mu\text{m}$, and $[\text{FeII}]26\ \mu\text{m}$ lines (*bottom row*) obtained with the *Spitzer* IRS–LL module (pixel scale $\sim 10.5''$). Crosses mark the position of the driving source HH211-mm. The dashed circle in the H_2 maps masks the area around a bright star (IC 348 IR) where line intensity measurements are unreliable. In the $[\text{FeII}]26\ \mu\text{m}$ map, contours are interrupted just before the eastern bowshock peak due to a rogue pixel. Contour levels in the $\text{H}_2\text{S}(1)$ map start from $10^{-12}\ \text{W cm}^{-2}\ \text{sr}^{-1}$ and increase in 10^{-13} increments, and from $7 \times 10^{-13}\ \text{W cm}^{-2}\ \text{sr}^{-1}$ with 5×10^{-14} increments for the $\text{S}(0)$ map. Contours of the ionic line maps start at $10^{-13}\ \text{W cm}^{-2}\ \text{sr}^{-1}$ with $10^{-13}\ \text{W cm}^{-2}\ \text{sr}^{-1}$ steps for $[\text{SiII}]$ and $[\text{FeII}]$, and at $10^{-13}\ \text{W cm}^{-2}\ \text{sr}^{-1}$ with $2 \times 10^{-13}\ \text{W cm}^{-2}\ \text{sr}^{-1}$ steps for $[\text{SI}]$.

Symmetrically on the redshifted side, the mid-IR H_2 emission close to the source forms an extended curving “finger” tracing both the jet and the cavity wall north of it, as seen in the near-IR (see Fig. 3) and peak R1 coincides with the near-IR knot F of McCaughrean et al. (1994). However, peak R2 is again centered on the cavity behind the bright bow rim traced in the near-IR. The spatial offset between B2 and R2 with respect to the near-IR counterparts suggests that mid-IR emission in these broad regions may be tracing the outer bow-shock wings where gas is expected to be in lower excitation conditions.

The top row of Fig. 4 presents the emission maps of the $\text{S}(0)$ – $\text{S}(1)$ rotational H_2 lines observed with the LL–IRS modules with a $10.5''$ sampling. Despite the lower angular resolution compared to the SL module, the $\text{H}_2\text{S}(1)$ line clearly delineates the same outflow pattern as in Fig. 3. As discussed in Sect. 2, faint extended diffuse emission is also present, and becomes mostly evident at the north end of the map; diffuse emission is even more apparent in the $\text{H}_2\text{S}(0)$ line map of Fig. 4.

This diffuse brightness may be caused by an extended photo-dissociation region (PDR) created at the cloud surface by the illumination of FUV radiation from nearby stars. The existence of a diffuse PDR is strongly supported by the detection of diffuse PAH emission, which is indicative of UV radiation in the field. The H_2 diffuse emission has a brightness of the order of $10^{-5}\ \text{erg/s/cm}^2$ for both the $\text{S}(0)$ and $\text{S}(1)$ lines: according to the Kaufman et al. (1999) model, this intensity is compatible with a PDR of density $10^4\ \text{cm}^{-3}$ or higher and a FUV field of the order of 10^2 times than the average interstellar field, measured in units of G_0 (i.e. in units of $1.6 \times 10^{-3}\ \text{erg cm}^{-2}\ \text{s}^{-1}$). The most likely candidate to produce the diffuse PDR is the Per B0.5 star, located at a projected distance of about $15'$ north of the HH211 system. The FUV field of this star (assuming an effective temperature of 25 000 K, Hernández et al. 2005), diluted for

the distance, can account for a $G_0 \sim 500$, which is compatible with the estimation given above, taking also into consideration projecting factors and partial field absorption along the path. We cannot exclude that part of the extended $\text{S}(0)$ and $\text{S}(1)$ H_2 emission also originates in other outflows located north and south of HH211-mm, seen in both optical and near-IR narrow band imaging of the region (Walawender et al. 2006; Eisloffel et al. 2003b). However, no close spatial correspondence is evident at our spatial resolution.

3.2. Atomic emission

The bottom row of Fig. 4 presents the emission line maps of $[\text{SiII}]35\ \mu\text{m}$, $[\text{SI}]25\ \mu\text{m}$, and $[\text{FeII}]26\ \mu\text{m}$ obtained from the LL–IRS modules with a $10.5''$ sampling. The emission from the atomic and ionic lines is substantially weaker than that of the H_2 lines. However, unlike H_2 lines that are not detected close to the driving source, all three fine structure transition contours are continuous, indicative of emission very close to the protostar HH211-mm. Morphologically, the $[\text{SI}]$ and $[\text{FeII}]$ maps peak at the blue lobe bow-shock¹. Emission from $[\text{SiII}]$ instead shows strong peaks on both the blue and red bow-shocks.

The enhanced atomic – ionic emission on the blue-lobe bow-shock is evidence of a highly energetic interaction of the underlying jet with the ambient material. In the same region, a wealth of other molecular and ionic lines such as OH, H_2O , HD and $[\text{NeII}]$ were mapped with *Spitzer* by Tappe et al. (2008), which collectively infer a strong UV flux typical of a $40\ \text{km s}^{-1}$

¹ In the $[\text{FeII}]26\ \mu\text{m}$ map, contours are interrupted just before the actual blue-shifted bowshock peak; this is an artifact resulting from a rogue pixel in the LL–IRS module that had to be masked out since it was introducing unreliable brightness values forming a bright vertical stripe across the map.

Fig. 5. Excitation diagrams of H_2 in various pixel sizes. (*Left*) H_2 columns in peak R1 from transitions in the SL module in $3.5''$ pixels (open circles). Ortho to para ratio and extinction are estimated from the alignment of the S(5) and S(3) data points with their neighboring S(2), S(4) and S(4), S(6) respectively. Dereddened columns (filled red circles) are linearly fitted (solid line) to derive the excitation temperature. Derived values are listed on the upper right corner of the diagram. (*Center, right*) Excitation diagrams of peaks R1+R2 and LL1 in $10.5''$ pixels, combining the H_2 transitions observed in both the LL and SL modules. The SL line maps were re-extracted at the LL map pixel scale. A second cooler component is apparent in S(0)–S(2) with $T_1 \sim 300$ K; the higher H_2 transitions trace a warmer component with temperature $T_2 \sim 1100$ K identical to that inferred at the SL pixel scale (see left panel).

dissociative shock. Such high velocity shocks in this region is also consistent with the detection of optical H_α and [SII] emission spots (Walawender et al. 2005, 2006). In the following, we demonstrate that rotational H_2 lines over the HH 211 outflow appear to trace slower shocks, either internal to the jet or in bow-shock wings.

4. Excitation conditions and mass fluxes

4.1. H_2 emission

4.1.1. Ortho to para ratio, extinction, and temperature components

The H_2 pure rotational transitions are easily thermalized in protostellar outflow environments owing to their low critical densities ($\sim 10^2$ – 10^4 cm^{-3}) and can be used to probe temperatures in the range between ~ 300 and 1500 K. The most direct way to estimate the temperature of the emitting gas is by means of an excitation diagram (EXD); this involves plotting the quantities $\ln(N_{u,J}/g_u)$ against $E_{u,J}$, where $N_{u,J}$ and $E_{u,J}$ are the column density and the energy of the upper level, and g_u the statistical weight including the spin degeneracy ($2S+1$). Considering LTE conditions, the values of these quantities for the observed H_2 transitions should fall on a straight line, from the inverse slope of which the excitation temperature can be derived. Deviations from this linear correlation can be used to constrain other physical properties, such as the H_2 ortho-to-para ratio (hereafter, OTP) and the optical extinction A_V , as described below.

Deviations of the OTP from its LTE value are reflected by vertical displacements between the ortho and para transitions in the EXD, forming a “saw-tooth” pattern between the two H_2 species. The observed OTP was estimated by examining the alignment of the S(5) data point with the neighboring S(4) and S(6) transitions, following the method outlined in Wilgenbus et al. (2000); in all cases, the spatial OTP variations are small, and values lie very close, within the statistical error limits, to the high-temperature LTE value of 3.

The H_2 S(3) transition at $9.7 \mu\text{m}$ is sensitive to the amount of dust along the line of sight, being located within a wide-band silicate absorption feature at the same wavelength; consequently, a visual extinction value can be estimated by comparing

the alignment of the S(3) point with those of S(2) and S(4), having previously corrected for any deviations of the OTP ratio from the equilibrium value. Visual extinction is then estimated by assuming an $A_{9.7}/A_V$ ratio equal to 0.087 (Rieke & Lebofsky 1985). A_V is found to exhibit no regular pattern along the outflow and to range between 7 and 9 mag, being consistent with previous estimates of 7–15 mag by McCaughrean et al. (1994) and Caratti o Garatti et al. (2006)².

Considering an average value of A_V equal to 8 mag across the map, we dereddened all the detected H_2 lines falling in the SL range (i.e. S(2) to S(7)) using the extinction law of Rieke & Lebofsky (1985). For all the points of the SL data cube where at least 3 H_2 lines are detected above 3σ confidence level, we calculated the excitation temperature from the slope of a least squares fit to the dereddened data points in the EXD. An example of these operations is shown in the left panel of Fig. 5 in the case of the R1 peak.

The results for the whole HH211 region are summarized in Fig. 6 in the form of an excitation temperature map. Common morphological characteristics between the excitation temperature map and the H_2 S(2)–S(7) emissions are evident; peaks in excitation temperature tend to coincide with peaks of emission. At those peaks, temperature reaches values up to 1200 K, while in the more diffuse outflow regions the temperature is as low as 700 K. In Table 1, we report the derived excitation temperatures with this method for the peaks of the S(5) emission along the blue and the red lobes of the outflow.

In addition to the “warm” H_2 component at ~ 1100 K indicated by the S(2)–S(7) lines, there is also evidence of a “cool” component from the S(0) and S(1) lines detected in the LL module. This is illustrated in the central panel of Fig. 5, which shows an EXD of the R1+R2 region in the LL $10.5''$ pixel, including the S(0) and S(1) datapoints. For consistency, the fluxes of S(2) to S(7) lines from the SL module were re-extracted at the coarser LL module sampling. Because of the extended diffuse emission, the S(0) line flux was obtained after subtracting the ambient contribution estimated in adjacent off-outflow regions.

While the resampled S(3)–S(7) emission retains the same “warm” temperature ~ 1100 K, the data points for the S(0)–S(2)

² O’Connell et al. (2005) reported a higher extinction of 25 mag in the redshifted lobe but considered their measurement as rather tentative given their observing conditions.

Table 1. Physical properties of the warm H₂ component from H₂ $v = 0-0$ S(2)–S(7) lines extracted at the SL (3.5'') scale.

Position	Offsets (")	H ₂ 0–0 S(5) (10 ^{–11} W cm ^{–2} sr ^{–1})	T (K)	$N(\text{H}_2)$ (10 ¹⁹ cm ^{–2})	$\dot{M}^a$ (10 ^{–7} $M_\odot$ yr ^{–1})
R1	[–20.1, 13.3]	3.3	1100 ± 70	1.15	1.1
R2	[–29.9, 17.0]	2.3	1050 ± 75	1.3	1.2
B1	[12.2, –4.7]	1.3	860 ± 40	1.1	1.1
B2	[26.9, –10.3]	2.0	950 ± 70	1.5	1.4
B3	[35.1, –10.6]	1.9	980 ± 75	1.4	1.4

Notes. ^(a) $\dot{M}$ is proportional to $(V_{\text{jet}}/100 \text{ km s}^{-1}) \times (3.5''/l_i)$ and is not corrected for postshock compression.

Table 2. Physical properties of the cool H₂ component from H₂ $v = 0-0$ S(0)–S(2) lines extracted at the LL (10.5'') scale.

Position	Offsets (")	H ₂ 0–0 S(1) (10 ^{–12} W cm ^{–2} sr ^{–1})	T (K)	$N(\text{H}_2)$ (10 ¹⁹ cm ^{–2})	$\dot{M}^a$ (10 ^{–6} $M_\odot$ yr ^{–1})
R1+R2	[–19.3, 15.1]	1.4	330 ± 50	7.5	2.0
LL1	[6.3, 2.0]	1.3	300 ± 45	7.8	2.8

Notes. ^(a) $\dot{M}$ is proportional to $(V_{\text{jet}}/100 \text{ km s}^{-1}) \times (10.5''/l_i)$ and is not corrected for post-shock compression.

Fig. 6. Excitation temperature map of the “warm” H₂ component deduced from the SL module map (3.5'' sampling). Temperature is derived by a linear fit to the dereddened columns from the $v = 0-0$ S(2) to S(7) lines; Peaks of S(5) emission from Fig. 2 are indicated. Pixels with less than 3 detected H₂ transitions are in black.

transitions show a steeper slope, which is evidence of a “cool” component at $T \sim 300$ K not probed by the higher J transitions. Another interesting result is that column densities obtained from the S(2)–S(7) lines in the LL pixel are smaller than in the SL pixel of 3.5'', indicating that the warm component does not fill the LL pixel.

A similarly resampled EXD towards the LL1 peak also reveals a cool component at 300 K, in addition to the warm component traced by the $J > 2$ lines. (see right-hand panel of Fig. 5). This resampling of the SL data was not possible at the LL peak B2+B3, as part of the corresponding LL pixel falls beyond the SL map coverage. This double temperature structure differs from a similar *Spitzer* analysis of the L1448 outflow where all $v = 0-0$ lines from S(0) to S(7) are interpreted in terms of a dominant, single temperature component at 600–900 K.

4.1.2. Column densities and mass fluxes

The total H₂ column density of the “cool” and “warm” components can be measured from the intersection of the linear fit to the data points in the EXD with the N/g axis, multiplied by the partition function $Z(T) = \sum g_i \exp(-E_i/kT)$. The latter is estimated for the given temperatures, summing up for the first 35 energy levels of H₂. Derived column densities for the two temperature components are reported in Tables 1 and 2 and range from $\sim 10^{19}$ for the warm component (averaged over the SL pixel size) to $8 \times 10^{19} \text{ cm}^{-2}$ for the cool component (averaged over the LL pixel size).

As already mentioned in the previous section, the inner peak of H₂ emission at B1/LL1 coincides with peaks of the underlying CO and SiO jet; it is therefore instructive to compare the H₂ column densities with those deduced from CO, taking into account the differing beam sizes, to investigate possible physical connections between the different tracers.

Lee et al. (2007) estimate an H₂ column towards the inner CO jet of $4-8 \times 10^{20} \text{ cm}^{-2}$ in their 1'' beam, assuming an excitation temperature of 100 K and a standard CO/H₂ abundance ratio of 8.5×10^{-5} (i.e. a fully molecular gas). If the H₂ mid-IR emission arises from the same narrow jet and is relatively uniform along the jet axis, our derived column densities have to be corrected for the different beam sizes across the jet by a factor = pixel size / 1''. This increases the H₂ columns to $\sim 3.5 \times 10^{19} \text{ cm}^{-2}$ for the “warm” component, and to $\sim 8 \times 10^{20} \text{ cm}^{-2}$ for the “cool” component. This latter value is in excellent agreement with the CO-derived one. This coincidence suggests that the “cool” H₂ gas detected by *Spitzer* towards LL1 could be tracing the same material as its CO equivalent, which would then indeed be *mostly molecular*. We also note that the temperature of 300 K of the cool H₂ matches that inferred from SiO line ratios in the jet (Hirano et al. 2006).

In contrast, the warm H₂ component column density corrected for beam dilution across the jet is 10 times lower than that of the CO jet. This may indicate that the warm H₂ emission close to the source arises only from a lower-density outer envelope around the CO jet. Alternatively, the warm H₂ component may trace thin shock-heated zones within the CO jet, thus filling only a fraction of the 3.5'' SL pixel length along the jet and being affected by additional beam dilution. We investigate the shock hypothesis in more detail in Sect. 4.2).

We may also determine a rough estimate of the one-sided mass flux of the cool and warm H₂ components, assuming a uniform laminar flow across the corresponding pixel, using the relationship from [Dionatos et al. \(2009\)](#)

$$\dot{M} = 2\mu m_{\text{H}} \times \langle N(\text{H}_2)A \rangle \times (V_t/l_t), \quad (1)$$

where $\mu = 1.4$ is the mean weight per gram of hydrogen, m_{H} is the proton mass, $N(\text{H}_2)$ the column density averaged over the area A of the pixel, l_t is the projected emitting length along the flow direction (assumed in Tables 1 and 2 to be equal to the pixel length), and V_t the tangential flow speed.

The value of V_t is quite uncertain. Taking into account the radial velocities in the range 5–20 km s^{−1} measured for the near-IR H₂ knots in the study of [Salas et al. \(2003\)](#), and assuming an inclination angle of between 5° and 10° (see Sect. 1), tangential velocities may vary within the range 30–230 km s^{−1}, introducing an absolute uncertainty of a factor 3 either way in the inferred $\dot{M}$ values. In the following, we adopt $V_t = 100$ km s^{−1} for ease of comparison with earlier work, bearing in mind that $\dot{M}$ values scale proportionally to the assumed velocity. In Col. 6 of Tables 1 and 2, we report the resulting $\dot{M}$ for the peaks of emission along the outflow, for both temperature components.

For the cool H₂ gas component, the laminar mass-flux is $\sim 20\text{--}28 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. For comparison, the one-sided jet mass-loss rate based on CO $J = 3\text{--}2$ emission obtained by [Lee et al. \(2007\)](#) is $3.5\text{--}7 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, assuming the same velocity of 100 km s^{−1} and a compression factor of 3. Adjusting their estimate for helium, and uncorrecting for compression, the laminar mass flux of the CO jet rises to $15\text{--}30 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$; this is in excellent agreement with the cool H₂ laminar mass flux estimated here, and is again consistent with fluxes both tracing the same fully molecular gas.

The warm H₂ laminar mass-flux is 15–30 times lower at $\sim 10^{-7} M_{\odot} \text{ yr}^{-1} \times (V_t/100 \text{ km s}^{-1})$. Similar mass-flux estimates were inferred from the pure rotational H₂ lines along the outflow of L1448 ([Dionatos et al. 2009](#), $0.5\text{--}1.4 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$), where similar H₂ columns were measured³. We note however that if the warm H₂ does not trace a laminar flow as assumed, but arises in a single shock within the pixel, then the relevant emitting length l_t along the flow will be generally narrower than the SL pixel size, and the true mass flux will be higher than listed in Table 1. Mass-fluxes of the warm component in the case of shock hypothesis are presented in the next section.

4.2. Shock models for the warm H₂ component

As pointed out in Sect. 4.1, peaks of warm ($J \geq 2$) H₂ emission coincide with peaks of temperature (Fig. 6) and possibly correspond to regions of shocked gas. To constrain the shock conditions in these regions, we employ the existing shock model grid described in the work of [Kristensen et al. \(2007\)](#), which is based on the MHD-VODE multi-fluid steady shock code of [Flower & Pineau des Forêts \(2003\)](#). The grid includes both continuous (C) and jump (J) type shocks and predicts the H₂ lines brightness for various values of pre-shock density ($n_{\text{H}}^{\text{ini}}$), shock velocity (V_s), initial OTP ratio (otp^{ini}), and transverse magnetic field density (φ). The ranges of parameters investigated here are

- $n_{\text{H}}^{\text{ini}} = 10^4$ to 10^7 cm^{-3} by alternating factors of 5 and 2;
- $V_s = 10\text{--}50 \text{ km s}^{-1}$ with a step of 1 km s^{-1} ;

- $otp^{\text{ini}} = 0.01, 1, 2, 3$;
- $\varphi(\mu G) = b \times \sqrt{n_{\text{H}}(\text{cm}^{-3})}$, where we fix $b = 1$ for C and $b = 0$ for J-type shocks.

The model is one-dimensional, considers 9 elements (H, He, C, O, N, S, Si, Mg, and Fe), and 136 species connected with 1040 reactions, and takes into account grain sputtering and erosion, as well as a variety of cooling and heating processes. Initial chemical abundances are computed assuming no UV field and an H₂ cosmic ray ionization rate of $5 \times 10^{-17} \text{ s}^{-1}$, yielding an ionization fraction $\sim 7 \times 10^{-8} (n_{\text{H}}^{\text{ini}}/10^4 \text{ cm}^{-3})^{-0.5}$. The H₂ level populations and line brightnesses are integrated along the post-shock cooling zone down to a temperature of 50 K, which is reached in a cooling time $\sim 100 (10^5 \text{ cm}^{-3}/n_{\text{H}}) \text{ yrs}$ in C-shocks (much shorter in J shocks). For more information about both the model and the grid data, the interested reader is referred to the articles of [Flower & Pineau des Forêts \(2003\)](#) and [Kristensen et al. \(2007\)](#).

We employed a χ^2 fitting method to optimally reproduce the observed H₂ emission selecting the most closely matching C or J-type steady shock models from the grid. The χ^2 – fitting is performed with and without considering the S(2) transition, since the latter may be dominated by the cool component (see Fig. 5).

4.2.1. C-shocks

As a general trend, we found that steady C-shock models are able to reproduce the observed S(2)–S(7) brightnesses only if we assume a small beam-filling factor. For this reason we applied our χ^2 fits to relative line brightnesses, scaled to the H₂ S(5) line; to obtain the best-fitting models, we then calculated a beam-filling factor as the average ratio of the observed to model line brightness.

In Fig. 7 we plot the EXDs of the best-fit χ^2 models for each preshock density, scaled by the corresponding beam filling factor, along with the observed data (filled circles) for the peak of emission R1; we note that beam-filling factors decrease for increasing values of density. There is a strong degeneracy among the models, with a very small spread in column densities for $n_{\text{H}}^{\text{ini}}$ in the range between 5×10^5 and 10^7 cm^{-3} and velocities in the range $10\text{--}13 \text{ km s}^{-1}$, although models for lower values of $n_{\text{H}} \leq 10^5$ and velocities up to 30 km s^{-1} cannot be excluded; each one of these models can account fairly well for the observed emissions.

Figure 8 presents the EXD of most closely matching C-type shocks (red squares, always scaled by the corresponding beam filling factor) along with the observed data points (filled circles), for the peaks of emission observed along the outflow. The input parameters of the models are reported in Table 3. All C-shock models predict moderate shock velocities ($10\text{--}15 \text{ km s}^{-1}$) and an initial ortho-to-para ratio at the high temperature LTE value of 3.

Steady C-shock models reproduce the data only if we consider low beam-filling factors $b_{\text{ff}} \sim 0.01\text{--}0.04$, or in other words a shock area $A_{\text{shock}} = A_{\text{pixel}} \times b_{\text{ff}}$, corresponding to a typical size of $\sqrt{A_{\text{shock}}} \sim 0.3''\text{--}0.7''$. These dimensions are comparable to the reported jet width $<1''$ in the interferometric CO and SiO maps of [Lee et al. \(2007\)](#). High post-shock densities in the same range as the best fit C-shock models ($5 \times 10^5\text{--}10^7 \text{ cm}^{-3}$) were retrieved in the jet by SiO emission studies ([Nisini et al. 2002b](#); [Hirano et al. 2006](#); [Lee et al. 2007](#)), supporting our modeling results. The shock models predict thin H₂ post-shock cooling zones of $0.015''\text{--}0.25''$, much smaller than the SL pixel size of $3.5''$, explaining the small warm column densities derived in the previous section. The cooling zone is also smaller than the

³ Note that a typographical error was introduced in Table 2 of [Dionatos et al. \(2009\)](#); the values of $N(\text{H}_2)$ are $\sim 7 \times 10^{18} \text{ cm}^{-2}$ at CS and $\sim 1.5\text{--}3.8 \times 10^{19} \text{ cm}^{-2}$ for the other positions.

Table 3. Parameters of best-fit shock models of the S(3) to S(7) lines.

Peak	C-shock ($b = 1$)				J-shock ($b = 0, b_{\text{ff}} = 1$)		
	$n_{\text{H}}^{\text{ini}} (\text{cm}^{-3})$	$V_s (\text{km s}^{-1})$	opr_{ini}	b_{ff}	$n_{\text{H}}^{\text{ini}} (\text{cm}^{-3})$	$V_s (\text{km s}^{-1})$	opr_{ini}
R1	$5 \times 10^5 - 10^7$	10–13	3	0.01–0.02	5×10^4	14	3
R2	$5 \times 10^5 - 10^7$	10–11	3	0.02–0.04	5×10^4	14	3
B1	$5 \times 10^5 - 10^7$	10	3	0.02–0.03	10^4	10	3
B2	$5 \times 10^5 - 10^7$	10–11	3	0.01–0.03	10^4	10	3
B3	$5 \times 10^5 - 10^7$	10–11	3	0.02–0.03	10^4	11	3

Fig. 7. Steady 1D C-shock model fits to the excitation diagram of the S(2)–S(7) lines at the peak of emission R1 in a 3.5'' pixel. Observed points (filled circles with 10% error bars) are displayed along with the best-fit χ^2 models for pre-shock densities between 10^4 and 10^7 cm^{-3} . The *top panel* lists the corresponding shock velocities and beam-filling factors, along with the reduced χ^2 fit values to the S(2)–S(7) ($J > 1$) and to the S(3)–S(7) ($J > 2$) H_2 transitions. A strong degeneracy among models is found (see text).

shock surface size inferred from the filling factor, as required for the 1D planar shock approximation to be locally valid.

If the warm H_2 emission indeed traces low-velocity internal shocks within a fast jet beam, we may infer that the jet mass-flux from the pre-shock density and the shock area is given by:

$$\dot{M}_{j,\text{shock}} = \mu m_{\text{H}} \times b_{\text{ff}} A_{\text{pixel}} \times n_{\text{H}}^{\text{init}} \times V_{\text{jet}}. \quad (2)$$

Considering a pre-shock density of $5 \times 10^5 \text{ cm}^{-3}$ with a beam filling factor b_{ff} of 0.023, and a jet speed of 100 km s^{-1} , for the warm H_2 we obtain $\dot{M}_{j,\text{shock}} = 7 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. This is 7 times higher than the value obtained in Sect. 4.1.2 assuming a laminar flow filling the SL pixel. The mass-flux entering the shock is only a factor of 3–4 below the laminar mass-flux for the cool H_2 (and CO). This discrepancy is expected in a time-variable flow undergoing internal shocks (Hartigan et al. 1994). Therefore, the

“warm” H_2 component seems compatible with localized heating in slow internal C-shocks within the molecular jet beam, and may not trace a separate lower density flow. We note that pre-shock densities higher than $5 \times 10^6 \text{ cm}^{-3}$ seem to be excluded, as the pre-shock mass-flux rate from Eq. (2) would become comparable to the accretion rate onto the HH211-mm driving source ($8 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ Lee et al. 2007).

However, SiO is observed only within $\sim 15''$ from the source, therefore pre-shock densities of $5 \times 10^5 \text{ cm}^{-3}$ may apply only to the B1 region. In addition, the H_2 emission in our maps remains unresolved only close to the driving source. Further out at the bow-shocks, the emission appears slightly resolved at the 3.5'' scale. A small $b_{\text{ff}} < 0.04$ would therefore imply that the bow-shock surface is highly patchy. This is a reasonable possibility, since HST observations in several outflows have shown that what appears to be an individual bow-shock at low resolution can be resolved into many substructures of sub-arcsec scale (e.g. HH2 in Orion, Bally et al. 2002). In HH211, SMA observations, performed with a resolution of $\sim 1''$ (Lee et al. 2007), show indeed that the CO emission is highly clumped, in both the high velocity jet and along the low velocity cavity ahead of the bow-shocks.

An alternative explanation of the small beam-filling factor in the outer HH211 bow-shocks might be that the pre-shock density drops to $\leq 10^4 \text{ cm}^{-3}$, so that the cooling length becomes comparable to the 3.5'' pixel size; the hypothesis underlining our model comparison, that the whole cooling zone fits inside the pixel, would then become invalid. Indeed, O’Connell et al. (2005) derived a low pre-shock density in the R1 and R2 regions by fitting a 3D C-type bow-shocks to the near-IR ro-vibrational H_2 lines. However, no predictions for the mid-IR H_2 emissions were provided. Extension to the 3D bow-shock geometry of the model applied here (Gustafsson et al. 2010) will be needed to perform more reliable modeling of the outer bowshocks of HH211 than possible in the present analysis.

A third possibility might be that the preshock gas ahead of the leading bowshocks is more ionized than we have assumed, because of the UV flux from nearby dissociative shocks such as that observed by Tappe et al. (2008) in the blue-shifted apex. This would increase the ion-coupling in the C-shock, reducing its width and column density, and yielding a larger filling factor. O’Connell et al. (2005) find that a high pre-shock ionization fraction of 10^{-5} and a high atomic hydrogen fraction of 20% provide a good fit to the near-IR lines in the redshifted bow. However, given the already high degeneracy of our model fits, and the lack of information about shock geometry and thickness in low angular resolution *Spitzer* maps, introducing the UV field as an additional free parameter is not feasible in practice. Additional constraints from other line tracers or from higher resolution mid-IR maps (eg. with JWST) will be required to explore this alternative.

Fig. 8. Excitation diagrams for all emission peaks mapped with the SL module; observed points (filled circles with error bars), are displayed along with best χ^2 fit C (red squares) and J (blue triangles) shock models. C- shock models can account fairly well for the observed emissions considering a small beam-filling factor, whereas J-shock models cannot reproduce well the slopes of the observed data points, except marginally in R1 and R2.

4.2.2. J-shocks and non-steady C-shocks

In the case of J-shocks, absolute brightness can be fairly well matched by models and beam-filling factors <1 were not necessary to be considered. The predicted pre-shock densities for J-shock models $\sim 1\text{--}5 \times 10^4 \text{ cm}^{-3}$ are lower than those of the best fit C-shock ones. As a general trend though, the best-fit J-shock models, represented by blue triangles in Fig. 8 and listed in Table 4, cannot reproduce at the same time the *slope* of the observed data points, except for the red-shifted bowshock (R1 and R2).

An analogous behavior was noted by Giannini et al. (2006), who used models produced by the same code of Flower & Pineau des Forêts (2003) to study the conditions of the HH54 outflow. Considering only the rotational H_2 emission in reported excitation diagrams, Giannini et al. (2006) found that steady C-type shocks overpredict the observed $v = 0$ column densities, whereas J-type shocks provide closer fits but cannot at the same time reproduce the observed slope. In the case of HH54, it is concluded that a non-steady, truncated C-shock with an embedded J-type front (C+J shock) optimally reproduces the observed H_2 emission. The same conclusion was also reached in the case of L1157 (Gusdorf et al. 2008a). The overall effect as clearly evident in excitation diagrams is to lower the column densities of low excitation energy levels (truncated C-precursor) and increase the column densities of the rovibrational energy levels of H_2 , excited in the J-type front (Flower et al. 2003). In our case, such models may fit our mid-IR data in the outer bowshocks without the need to consider a beam filling factor <1 . A more detailed comparison with unsteady C+J-shock models would be needed to test this possibility, although such models were not included in our

adopted grid as the age of the shock would have, again, added an extra free parameter to already degenerate fits. The shock ages would have to be much shorter than the outflow dynamical age of about 1000 yrs to reduce by a factor of 50 the warm H_2 column (typically a shock age of $1/50$ of the H_2 cooling time, i.e. $\sim 2 (10^5 \text{ cm}^{-3}/n_{\text{H}})$ yrs).

4.3. Atomic emission

As pointed out in section Sect. 3, all atomic/ionic emission falls within the LL IRS module and consequently these maps are of lower spatial resolution than the SL ones. Since atomic emission is found to be enhanced at the bow shocks but remains significant also close to the driving source, we focused our analysis along the jet axis including the intermediate points LL1 and LL2 (see Fig. 4) between the bow shocks, where the $[\text{FeII}] 26 \mu\text{m}$ line is detected. To analyze the ionic emission, we followed the method employed by Dionatos et al. (2009), and the reader is referred to this article for a detailed description.

4.3.1. Electron density

As a first step, the observed emissions of $[\text{SiII}]$ and $[\text{FeII}]$ were employed to constrain the electron density. In Fig. 9, the ratio of $[\text{SiII}]34.8 \mu\text{m}$ to $[\text{FeII}]26.0 \mu\text{m}$ as a function of the electron density is presented, for temperatures of 500 K, 1000 K, and 4000 K (solid and dashed lines). A statistical equilibrium model was employed that uses the first 16 levels for $[\text{FeII}]$ (Nisini et al. 2002a), and a two level system was considered for $[\text{SiII}]$, for which radiative and collisional rates with electrons were taken from

Table 4. Physical properties of the atomic/ionic line component.

Position	Offsets ($''$)	[SI] (10^{-13} Watt cm^{-2} sr^{-1})	[FeII]/[SI]	[SiII]/[FeII]	$\dot{M}(\text{[SI]})^{a,b}$ ($10^{-7} M_{\odot} \text{yr}^{-1}$)	$n_{\text{H}}^{b,c}$ (10^5cm^{-3})
R1+R2	[−19.3, 15.1]	5.34 ± 0.13	0.92 ± 0.04	2.18 ± 0.51	0.4–3.4	0.21–1.61
LL1	[−6.5, 8.6]	6.24 ± 0.16	0.60 ± 0.02	1.77 ± 0.82	0.4–4.1	0.24–1.88
LL2	[6.3, 2.0]	7.49 ± 0.19	0.35 ± 0.01	1.95 ± 0.93	0.7–4.9	0.29–2.91
B2+B3	[31.9, −11.0]	16.1 ± 0.41	0.37 ± 0.01	2.14 ± 0.42	1.3–10.5	0.62–4.9

Notes. ^(a) $\dot{M}$ is proportional to $(V_{\text{jet}}/100 \text{ km s}^{-1}) \times (10.5''/l_i)$ and is not corrected for postshock compression. ^(b) values calculated for collisions with electrons at $T = 3000 \text{ K}$ (lower value) and $T = 700 \text{ K}$ (upper value); including collisions with hydrogen for $n(\text{H}) = 10^4 \text{ cm}^{-3}$ would decrease the minimum and maximum values by a factor of ~ 2 and 4, respectively. ^(c) average proton density assuming an emitting volume of $10.5'' \times 1'' \times 1''$.

Fig. 9. Diagnostic diagram of the $[\text{SiII}]35 \mu\text{m}/[\text{FeII}]26 \mu\text{m}$ ratio versus electron density, for temperatures of 500 K, 1000 K, and 4000 K (solid and dashed lines) and assuming a solar Si^+/Fe^+ abundance ratio. The hatched area represents the observed ratio for the north and south bow-shock regions, from which electron densities between ~ 100 and 400 cm^{-3} are found.

Dufton & Kingston (1991); a solar abundance ratio of Si^+/Fe^+ was considered, taking into account the similar ionization potential of the two species and the similar sputtering efficiencies of Si and Fe atoms from olivine grains in C-shocks, according to Fig. 2 of Gusdorf et al. (2008b). In the diagram, we plot the observed ratio limits at the bow shocks for clarity, but the results for the other points along the jet are similar and are listed in Table 4. Lower limits to the electron density vary between 40 and 150 cm^{-3} for temperatures of 4000 K and 500 K, respectively, while upper limits converge for the considered temperatures to $\sim 400 \text{ cm}^{-3}$. Temperature limits lower than a few thousand K are reported in the work of Tappe et al. (2008) for the blue-shifted bow shock considering a non-LTE analysis of the three $[\text{FeII}]$ lines ($18 \mu\text{m}$, $26 \mu\text{m}$, and $35 \mu\text{m}$) that are detected with the high resolution IRS modules. Based on this, we restricted the electron density lower limit to 100 cm^{-3} by assuming a maximum temperature of 3000 K.

4.3.2. Gas phase depletion

We investigate the depletion onto grains following the analysis of Dionatos et al. (2009). We calculate the gas phase abundance of refractory elements such as iron and silicon by comparing their emissions with the emission of a non-refractory species, which in the present case is sulphur. Theoretical emissivities of sulphur were calculated by considering a five level

Fig. 10. Diagnostic diagram of $[\text{FeII}]26 \mu\text{m}/[\text{SI}]25 \mu\text{m}$ ratio versus temperature assuming solar relative abundances. Electron densities of 100 and 400 cm^{-3} are considered (full and dotted lines, respectively). The effect of collisions with atomic hydrogen on the $[\text{SI}]$ excitation is also shown (long-dashed line, $n(\text{H}) = 10^4 \text{ cm}^{-3}$). The observed ratios are always below the predicted values for solar abundances, which is interpreted as iron being depleted onto dust-grains in the considered regions.

statistical equilibrium code for an upper temperature limit of 3000 K assumed from the work of Tappe et al. (2008) and a lower limit of 700 K imposed by the H_2 analysis. For the excitation of sulphur, we also calculated the emissivities due to collisions with atomic hydrogen, taking into account that in environments of low ionization fraction and high total density such excitation may prove to be significant, despite the collisional de-excitation rates for atomic hydrogen being lower than the electronic ones (Hollenbach & McKee 1989, $\gamma_{\text{H}}/\gamma_{\text{e}} \sim 0.02$) for the $[\text{SI}]25 \mu\text{m}$ line. For these calculations, we considered a medium in which $n(\text{H}) = 10^4 \text{ cm}^{-3}$. The excitation of $[\text{FeII}]$ and $[\text{SiII}]$ by H-collisions was not taken into account because neutral hydrogen collisional rates are far less important for ions (i.e. $\sim 10^3$ – 10^4 weaker than electronic collisional rates), and are not available for all the levels considered in our model.

The results of these calculations are illustrated in Fig. 10, where we plot the ratio of $[\text{FeII}] 26 \mu\text{m}$ to $[\text{SI}]25 \mu\text{m}$ against gas temperature for electron densities of 100 and 400 cm^{-3} , assuming that iron is fully ionised (which is the case in most dissociative shocks) and has a solar abundance. The observed ratios for the points R1+R2 and B1+B2 are way below the expected values, giving rise to the hypothesis that iron is heavily depleted onto dust grains in the considered regions, more so if the emitting gas is cooler. The case including atomic hydrogen collisions with $n(\text{H}) = 10^4 \text{ cm}^{-3}$ is plotted separately in Fig. 10. The iron

Table 5. Gas phase abundance of Fe⁺ and Si⁺ from line ratios to sulphur.

Position:	R1+R2	LL1	LL2	B2+B3
[Fe ⁺ _{gas}]/[Fe _⊙] ^a	4–9 × 10 ⁻²	3–6 × 10 ⁻²	2–4 × 10 ⁻²	2–4 × 10 ⁻²
[Fe ⁺ _{gas}]/[Fe _⊙] ^b	10–20 × 10 ⁻²	7–10 × 10 ⁻²	5–7 × 10 ⁻²	5–7 × 10 ⁻²
[Si ⁺ _{gas}]/[Si _⊙] ^a	4–9 × 10 ⁻²	2–4 × 10 ⁻²	1.5–3 × 10 ⁻²	2–4 × 10 ⁻²
[Si ⁺ _{gas}]/[Si _⊙] ^b	10–20 × 10 ⁻²	5–8 × 10 ⁻²	3–6 × 10 ⁻²	4–7 × 10 ⁻²

Notes. ^(a) assuming only collisions with electrons ($n_e = 100$ – 400 cm^{-3}) and $T_e = 700 \text{ K}$ (lower value) and 3000 K (upper value). ^(b) including excitation of sulfur by atomic hydrogen with $n(\text{H}) = 10^4 \text{ cm}^{-3}$.

depletion is less severe in this case but still substantial at about a factor 10.

In Table 5, we provide the inferred gas phase depletion for temperatures of 700 and 3000 K, both without and with atomic hydrogen excitation of [SI]. The gas phase abundance of Fe⁺ is about 2–20% of the solar value for $T = 3000$ and 700 K , respectively, for all the points under examination. Similarly low values were also found in the case of the L1448 jet (5–20%). Identical gas-phase depletions are obtained for Si⁺, but since we assumed a solar Fe⁺/Si⁺ ratio in the first place to derive our n_e values, this is just a self-consistency check. Interestingly, the SiO abundance in the HH211 molecular jet, estimated to be $\sim 10^{-6}$ by Nisini et al. (2002b) and Chandler & Richer (2001), corresponds to 3% of the solar abundance of silicon, therefore the fraction of silicon released in the gas phase seems comparable in the atomic and molecular components of HH211.

4.3.3. Density and mass flux of the atomic component

The total number of H nuclei in the emitting volume V can be derived from the line luminosity according to the relation

$$n_{\text{H}} V = L(\text{line}) \left(h\nu A_i f_i \left[\frac{X}{H} \right] \right)^{-1}, \quad (3)$$

where A_i and f_i are the spontaneous radiative decay rate and fractional population of the upper level, and $[X/H]$ is the gas phase abundance of the atom/ion under consideration with respect to H nuclei. Line luminosities were integrated over the LL pixel size area, and the fraction of atoms at the upper level f_i was calculated for n_e between 100 and 400 cm^{-3} and $T = 700$ – 3000 K as derived by the previous analysis.

This relation was applied to [SI], the only non-refractory species detected, assuming that all Sulphur is in neutral form and employing its solar abundance (Asplund et al. 2005). These calculations for refractory species would be redundant, because their gas phase abundances from Table 5 were determined from their intensity ratio with respect to [SI].

Values of n_{H} at individual positions are listed in Col. 7 of Table 4 assuming an emitting volume in the LL pixel of $10.5'' \times 1'' \times 1''$ (uniform narrow jet). The inferred n_{H} depends strongly on the adopted excitation conditions: it is about 0.2 – $0.6 \times 10^5 \text{ cm}^{-3}$ for $T = 3000 \text{ K}$, $n_e = 100 \text{ cm}^{-3}$, and 8 times higher for $T = 700 \text{ K}$, $n_e = 400 \text{ cm}^{-3}$. The ionisation fraction is then 1.6 – 5×10^{-3} at 3000 K , or a factor of two lower at 700 K . This ionization level appears to agree with the upper temperature, and therefore the lower density range. If the fraction of H atoms is important for $n(\text{H}) \simeq 10^4 \text{ cm}^{-3}$, the n_{H} values would be reduced further by a factor 2, to a few 10^4 cm^{-3} . In the case again, that the emission comes from a smaller volume, e.g. a small $1''$ knot as observed in the near-IR [FeII] $1.64 \mu\text{m}$ line, the density would increase to 10^5 cm^{-3} .

The mass flux in the atomic/ionic component assuming a laminar flow can also be derived by applying the relationship given in Nisini et al. (2005) applied to the mid-IR lines in Dionatos et al. (2009)

$$\dot{M} = \mu m_{\text{H}} \times (n_{\text{H}} V) \times (V_t/l_t), \quad (4)$$

where $\mu = 1.4$ is the mean weight per H nucleus, m_{H} is the proton mass, $n_{\text{H}} V$ is the total number of protons in the emitting region as given by Eq. (3), l_t is the projected emitting length along the flow, and V_t is the tangential flow velocity.

Derived mass-flux values at the various emission peaks are listed in Col. 6 of Table 4 for a tangential speed of 100 km s^{-1} and $l_t = 10.5''$ (LL pixel size). As for $n_{\text{H}} V$, they again depend strongly on the adopted excitation conditions. On the basis of the ionization fraction considerations presented above, we adopt the high-temperature, smaller $\dot{M}$ values of ~ 0.4 – $1 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. These are 20–50 times lower than the cool H₂ jet mass-flux, assuming the same flow speed of 100 km s^{-1} .

However, we emphasize again that $\dot{M}$ estimates assuming a laminar jet flow may be incorrect if the [SI] emission arises from shocks, which is likely given the ionization fraction inferred above. This is difficult to ascertain without the use of appropriate shock models.

The atomic/ionic emission appears to require higher excitation shocks than those producing the mid-IR H₂ lines. The low-velocity 10 – 15 km s^{-1} shock models that most accurately reproduce the warm H₂ emission are unable to reproduce also the observed [FeII] and [SiII] line intensities unless the shocks are of J-type and these atoms are essentially undepleted. As discussed in Sect. 4.3.2, there is overwhelming evidence of the depletion of these refractory species, so [FeII] and [SiII] probably originates from faster shocks than those dominating the mid-IR H₂ lines. It is indeed likely that the mid-IR atomic lines originates from the same dissociative shocks at $v_s \geq 30 \text{ km s}^{-1}$ that produce the optical and NIR emission of H α , [SII], and [FeII] (O’Connell et al. 2005; Caratti o Garatti et al. 2006; Walawender et al. 2006, 2005).

Unfortunately, our shock models do not yet include ionization and dissociation by the shock UV flux, so we cannot explore the relevant excitation range. However, we note that the J-shock models of Hollenbach & McKee (1989), which include UV flux, suggest that the [SI] $25 \mu\text{m}$ brightness is relatively independent of shock speed over the range 30 – 100 km s^{-1} and is roughly proportional to $n_{\text{H}}^{\text{ini}}$. Our measured flux inside the LL $10.5''$ pixel implies that $n_{\text{H}}^{\text{ini}} \times b_{\text{ff}} \simeq 100$ – 1000 cm^{-3} . From Eq. (2), we would infer a preshock mass-flux of ~ 0.5 – $5 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$, which is lower still by a factor 4–40 than the cool H₂ jet mass-flux.

These results suggest that the atomic component in the HH211 jet does not have enough momentum flux to entrain the CO/SiO/H₂ jet, if their velocities are comparable and the shock compression in the cool H₂/CO component does not exceed a factor of 3. The molecular jet would then have to trace material ejected from the accretion disk, while the atomic component would trace a separate ejection, e.g. from hotter more internal regions of the accretion disk. On the other hand, a higher compression factor in the cool H₂/CO emitting zone, or a faster ionic jet would suffice to remove this discrepancy, therefore a definite conclusion on whether the molecular jet is ejected or entrained cannot be reached from the present data alone.

5. Conclusions

We have carried out *Spitzer* spectral mapping observations towards the jet driven by the Class 0 source HH211-mm.

Molecular lines (pure rotational H_2) as well as fundamental atomic and ionic lines ([SI], [SiII], [FeII]) have been detected, and their maps follow the characteristic bipolar outflow pattern traced by near-IR H_2 and CO lines. The H_2 emission becomes important only $5''$ away from the driving source, while atomic and ionic lines are detected very close to the protostar. In the inner part of the blue-shifted lobe, the H_2 emission was found to be spatially coincident with the high velocity jet observed in both CO and SiO.

Our analysis of the observed H_2 lines revealed two temperature components: “cool” gas at $T \sim 300$ K dominating the mass, and “warm” gas at $T \sim 700\text{--}1200$ K of 10 times lower average column density. Once corrected for beam dilution, the column density of “cool” H_2 towards the CO jet is compatible with hydrogen being mostly molecular. The warmer component traced by the S(2) to S(7) lines is well fitted by C-shock models of high density $\approx 5 \times 10^5$ and a small shock-cross section of $0.5''$, compatible with the density and width of the CO jet quoted by Lee et al. (2007). The warm H_2 emission could then trace thin layers of warm post-shock gas within the CO jet.

High-density C-shock models may also account for the brightness of the H_2 mid-IR emission further downwind beyond the CO and SiO jet, but the small shock surface filling factor of 0.01–0.04 is not easy to reconcile with the spatial extension visible in *Spitzer* maps, unless the bow-shock wings are very clumpy. Lower density shocks of $n_{\text{H}} \leq 10^4 \text{ cm}^{-3}$, where the cooling zone spreads over several pixels and/or higher preshock ionization may need to be considered in these regions, as previously done when modeling near-IR H_2 excitation in the red-shifted bow-shock of HH211 (O’Connell et al. 2005).

The detected fine structure lines mapped very close to the driving source are indicative of an embedded atomic jet. Line ratio diagnostics indicate a gas-phase depletion of iron and silicon of at least a factor of 10, and lower excitation conditions than in optically visible jets. An atomic jet of similar properties was also detected by *Spitzer* in the outflow of L1448-C (Dionatos et al. 2009). As suggested in that case, the detected atomic gas in the HH211-mm outflow may represent the equivalent of the forbidden emission line (FEL) region observed in more evolved Class I/II sources. The gas depletion of iron and silicon indicates that dust grains have survived in the atomic flow, ruling out an origin from within the dust sublimation zone close to the protostar. The excitation conditions require faster shocks than those producing the H_2 mid-IR lines.

Estimations of the molecular and atomic mass-flux rates have been performed using both a laminar flow assumption and shock models. The cool H_2 mass-flux is comparable to that inferred from CO observations, with a value uncorrected for compression of $\sim 2 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ ($V/100 \text{ km s}^{-1}$); a similar value is found for the warm H_2 if it arises from dense C-shocks as suggested by best-fit models. The atomic component mass-flux is uncertain by a factor of 8 due to its uncertain temperature, but considerations of the ionization fraction as well as published dissociative shock models imply a lower mass-flux than in the molecular jet. However, the momentum fluxes could become comparable if the atomic jet is faster than the molecular jet, or if the cool H_2 and CO are affected by shock compression. Given the uncertainties, it remains unclear whether the molecular CO jet traces ambient gas entrained by the atomic jet, or if it has to be ejected, for example in a molecular MHD disk wind as modeled by Panoglou et al. (2010).

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