SPITZER SPECTRAL LINE MAPPING OF PROTOSTELLAR OUTFLOWS. II. H$_2$ EMISSION IN L1157

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ABSTRACT

We present an analysis of Spitzer-IRS spectroscopic maps of the L1157 protostellar outflow in the H$_2$ pure-rotational lines from S(0) to S(7). The aim of this work is to derive the physical conditions pertaining to the warm molecular gas and study their variations within the flow. The mid-IR H$_2$ emission follows the morphology of the precessing flow, with peaks correlated with individual CO clumps and H$_2$ 2.12 mm ro-vibrational emission. More diffuse emission delineating the CO cavities is detected only in the low-laying transitions, with $J_{\text{lower}} \leq 2$. The H$_2$ line images have been used to construct two-dimensional maps of N(H$_2$), H$_2$ ortho-to-para ratio (OPR), and temperature spectral index $\beta$, in the assumption of a gas temperature stratification where the H$_2$ column density varies as $T^{-\beta}$. Variations of these parameters are observed along the flow. In particular, the OPR ranges from ~0.6 to 2.8, highlighting the presence of regions subject to recent shocks where the OPR has not had time yet to reach the equilibrium value. Near-IR spectroscopic data on ro-vibrational H$_2$ emission have been combined with the mid-IR data and used to derive additional shock parameters in the brightest blueshifted and redshifted emission knots. A high abundance of atomic hydrogen ($H/H_2 \sim 0.1$–0.3) is implied by the observed H$_2$ column densities, assuming $n$(H$_2$) values as derived by independent SiO observations. The presence of a high fraction of atomic hydrogen indicates that a partially dissociative shock component should be considered for the H$_2$ excitation in these localized regions. However, planar shock models, either of C- or J-type, are not able to consistently reproduce all the physical parameters derived from our analysis of the H$_2$ emission. Globally, H$_2$ emission contributes to about 50% of the total shock radiated energy in the L1157 outflow. We find that the momentum flux through the shocks derived from the radiated luminosity is comparable to the thrust of the associated molecular outflow, supporting the scenario where the latter is driven by the shock working surface.

Key words: ISM: jets and outflows – stars: formation

Online-only material: color figures

1. INTRODUCTION

The interaction of protostellar outflows with the ambient molecular cloud occurs through radiative shocks that compress and heat the gas, which in turn cools down through line emission at different wavelengths. In the dense medium where the still very embedded protostars (the so-called class 0 sources) are located, shocks are primarily non-dissociative, and hence the cooling is mainly through emission from abundant molecules. Molecular hydrogen is by far the most abundant species in these environments, and although H$_2$ emits only through quadrupole transitions with low radiative rates, it represents the main gas coolant in flows from young protostars. H$_2$-shocked emission in outflows has been widely studied in the past through its ro-vibrational emission in the near-IR (e.g., Eisloffel et al. 2000; Giannini et al. 2004; Caratti o Garatti et al. 2006) that traces the dense gas at $T \sim 2000$–4000 K. Most of the thermal energy associated with the shocks is however radiated away through the emission of H$_2$ rotational transitions of the ground-state vibrational level at $\lambda < 28 \mu$m (e.g., Kaufman & Neufeld 1996). Mid-IR H$_2$ lines are easily excited at low densities and temperatures between 300 and 1500 K; therefore, they are very good tracers of the molecular shocks associated with the acceleration of ambient gas by matter ejection from the protostar. Given the low excitation temperature, they can also probe regions where H$_2$ has not yet reached the ortho-to-para (OPR) equilibrium, thus giving information on the thermal history of the shocked gas (Neufeld et al. 1998; Wilgenbus et al. 2000). In addition, given the different excitation temperature and critical densities of the $v = 0$–0 and $v \geq 1$ H$_2$ lines, the combination of mid-IR with near-IR observations is a very powerful tool to constrain the global physical structure and the shock conditions giving rise to the observed emission.

The study of the 0–0 rotational emission in outflows started in some detail with the Infrared Space Observatory (ISO). Thanks to the observations performed with the Short Wavelength Spectrometer (SWS) and ISO-CAM instruments, the shock conditions, the OPR and the global H$_2$ cooling have been derived in a handful of flows (e.g., Neufeld et al. 1998; Nisini et al. 2000; Molinari et al. 2000; Lefloch et al. 2003). More recently, the InfraRed Spectrograph (IRS; Houck et al. 2004) on board Spitzer, with its enhanced spatial resolution and sensitivity with respect to the ISO spectrometers, has been used to obtain detailed images of the H$_2$ rotational emission, from S(0) to S(7), of several outflows, from which maps of important physical parameters, such as temperature, column density, and OPR, have been constructed (Neufeld et al. 2006; Maret et al. 2009; Dionatos et al. 2010). In this framework, Neufeld et al. (2009, hereafter N09) have recently presented IRS spectroscopic maps observations of five young protostellar outflows at wavelengths between 5.2 and 37 $\mu$m, and discussed their averaged physical properties and overall energetics. In all the flows, the $H_2$ S(0)–S(7) emission has been detected and contributes to more than 95% of the total line luminosity in the
5.2–37 μm range, while atomic emission, in the form of Fe II and S I fine structure lines, accounts for only the remaining ∼5%. In the present paper, we will analyze the H2 line maps obtained by N09 toward the L1157 outflow, with the aim of deriving the main physical conditions pertaining to the molecular gas and their variations within the flow. This in turn will give information on the thermal history of the flow and on how energy is progressively transferred from the primary ejection event to the slow moving ambient gas. For this first detailed analysis, L1157 has been chosen among the sources observed by N09 given its uniqueness as a very active and well-studied flow at different wavelengths. More than 20 different chemical species have indeed been detected in the shocked spots of this object (Bachiller & Perez Gutierrez 1997; Benedettini et al. 2007), some of them for the first time in outflows (e.g., HNCO; Rodriguez-Fernández et al. 2010, and complex organic molecules; Arce et al. 2008; Codella et al. 2009), testifying for a rich-shock-induced chemistry. Warm H2-shocked emission in L1157 is also evidenced through near-IR maps (e.g., Davis & Eisloeffel 1995) and Spitzer-IRAC images (Looney et al. 2007). The L1157 outflow has also recently been investigated with the Herschel Space Observatory, and was shown to also be very strong at far-IR wavelengths (Codella et al. 2010; Lefloch et al. 2010; Nisini et al. 2010).

The L1157 outflow extends about 0.7 pc in length. Its distance is uncertain and has been estimated between 250 and 440 pc. Here we will adopt D = 440 pc for an easier comparison with other works. The outflow is driven by a highly embedded, low-mass class 0 source (L1157 mm or IRAS20386+6751) having $L_{\text{bol}} \sim 8.3 L_{\odot}$ (Froebrich 2005). It is a very nice example of an outflow driven by a precessing and pulsed jet, possessing an S-shaped structure and different cavities, whose morphology has been reproduced assuming that the outflow is inclined by ∼80° to the line of sight and the axis of the underlying jet precesses on a cone of 6° opening angle (Gueth et al. 1996). The episodic mass ejection events are evidenced by the presence, along the flow, of individual clumps that are symmetrically displaced with respect to the central source. It is therefore a very interesting target for a study of the physical conditions pertaining to these active regions through an H2 excitation analysis.

The paper is organized as follows. The observations and the main results are summarized in Section 2. In Section 3, we describe the analysis performed on the H2 images to derive maps of temperature, column density and OPR. A more detailed NLTE analysis on individual emission peaks is also presented here, where the Spitzer data are combined with near-IR data to further constrain the excitation conditions. The implications of these results for the shock conditions along the L1157 flow are discussed in Section 4, together with an analysis of the global energy budget in the flow. A brief summary follows in Section 5.

### 2. OBSERVATIONS AND RESULTS

Observations of the L1157 outflow were obtained in 2007 November with the IRS instrument, during Cycle 4 of the Spitzer mission. The full IRS spectral range (5.2–36.5 μm) was observed with the long–high (LH), short–high (SH; $R \approx 600$), and short–low (SL; $R$ between 64 and 128) modules. The L1157 outflow region was covered through five individual IRS maps of ∼1′ × 1′ of size each, arranged along the outflow axis. Each map was obtained by stepping the IRS slit by half of its width in the direction perpendicular to the slit length. For the SH and LH modules, the slit was also stepped parallel to its axis by 4/5 (SL) and 1/5 (LH) of its length. Details on the data reduction that generated the individual line maps from the IRS scans are given in N09. The final maps have been resampled to a grid of 2′′ spacing allowing a pixel by pixel comparison of maps obtained with the different IRS modules. Maps of the brightest detected lines as well as the full spectrum in a representative position are shown in Figures 7 and 12 of N09. As regards to H2, all the pure rotational lines of the first vibrational levels, from S(0) to S(7), are detected at various intensities along the flow. Each map was obtained by stepping the IRS slit by half of its width in the direction perpendicular to the slit length. The presence of S(0) and S(1) is very similar, with peaks of mid-IR emission located at the near-IR knots from A to D, as identified by Davis & Eisloeffel (1995). When compared with the CO map, the mid-IR H2 emission appears to follow the curved chain of clumps (labeled as B0–B1–B2 and R0–R1–R, for the blueshifted and redshifted lobes, respectively) that also correspond to peaks of SiO emission, as resolved in interferometric observation by Gueth et al. (1998) and

| Transition | λ(μm) | Module | Intensitya (10⁻⁵ erg cm⁻² s⁻¹ sr⁻¹) |
|------------|-------|--------|-------------------------------|
| S(0) J = 2–0 | 28.21 | LH | (20, –56) | (–2, +30) | (–32, +58) | (–26, +14) | (–30, +14)b |
| S(1) J = 3–1 | 17.03 | SH | 4.47 | 0.43 | 3.23 | 3.50 | 4.30 |
| S(2) J = 4–2 | 12.28 | SH | 8.70 | 0.30 | 4.05 | 6.63 | 7.95 |
| S(2) J = 4–2 | 12.28 | SL | 7.05 | 0.34 | 3.58 | 4.39 | 7.11 |
| S(3) J = 5–3 | 9.66 | SL | 21.85 | 1.82 | 14.61 | 9.38 | 17.86 |
| S(4) J = 6–4 | 8.02 | SL | 12.89 | <2.1c | 5.38 | 5.47 | 8.30 |
| S(5) J = 7–5 | 6.91 | SL | 27.34 | 1.76 | 11.91 | 6.72 | 12.74 |
| S(6) J = 8–6 | 6.11 | SL | 5.74 | <1.3c | 3.00 | 3.32 | 3.30 |
| S(7) J = 9–7 | 5.51 | SL | 18.11 | 0.97 | 6.63 | 3.35 | 3.10 |

Notes.

- a Intensity averaged within a 20′′ FWHM Gaussian aperture around the considered position. Absolute errors are of the order of 20%.
- b Offsets in arcsec with respect to the L1157 mm source. These positions are associated with individual near-IR/mm emission clumps, as indicated in Table 2.
- c 2σ upper limit.
Figure 1. L1157 maps of the 0–0 S(1)17.035 μm and S(2)12.29 μm lines observed with the Spitzer-IRS-SH module. In both images, contours are displayed in steps of 10% of the peak intensity value, which is $8.2 \times 10^{-5}$ and $1.9 \times 10^{-4}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$ for the S(1) and S(2) maps, respectively. The average rms noise in the two images is of the order of $1.5 \times 10^{-6}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 2. Left: the map of the 1–0 S(5) line at 6.9 μm with superposed contours of the integrated CO (2–1) emission (from Bachiller et al. 2001). The positions of the molecular condensations (bullets) identified in Bachiller et al. (2001) are labeled. Right: the map of the 1–0 S(1) line at 2.12 μm (Caratti o Garatti et al. 2006). The main group of NIR knots, labeled from A to D according to Davis & Eislöffel (1995), is indicated.

(A color version of this figure is available in the online journal.)

Zhang et al. (2000). The L1157 outflow morphology has been suggested to delineate a precessing flow (Gueth et al. 1996), where the H$_2$ and SiO peak emission knots follow the location of the actual working surface of the precessing jet and are thus associated with the youngest ejection episodes. Diffuse H$_2$ emission is also detected in the S(1)–S(2) maps, that delineates the wall of a cavity that connects the central source with both the R0 and B0 clumps. Such a cavity has been recognized in
the CO 1–0 interferometric maps and it is likely created by the propagation of large bow shocks. The S(1)–S(2) maps of Figure 1 show extended emission of H$_2$ also in the southeast (SE) direction (i.e., where the B2 clump is located) and in the eastern edge of the northern lobe, that also follow quite closely the CO morphology: these regions at lower excitation might trace additional cavities created by an older ejection episode of the precessing jet.

3. H$_2$ ANALYSIS

3.1. LTE 2D Analysis of the Rotational Lines: Maps of Averaged Parameters

We have used the H$_2$ line maps to obtain the two-dimensional distribution of basic H$_2$ physical parameters, through the analysis of the rotational diagrams in each individual pixel. As described in N09, who analyzed the global H$_2$ excitation conditions in L1157, the distribution of upper-level column densities of the S(0)–S(7) lines as a function of their excitation energy, does not follow a straight line, indicating that a temperature stratification in the observed medium exists. The exact form of this temperature stratification depends on the type of shock the H$_2$ lines are tracing, as they probe the post-shock regions where the gas cools from $\approx 1000$ K to $\approx 200$ K.

The simplest way to parameterize the post-shock temperature stratification is to assume a power-law distribution: this approach was applied by Neufeld & Yuan (2008), who also show that this type of distribution is expected in gas ahead of unresolved bow shocks. On this basis, and also following N09, we fit the observations assuming a slab of gas where the H$_2$ column density in each layer at a given $T$ varies as $dN \propto T^{-\beta}dT$.

This law is integrated, to find the total column density, between a minimum ($T_{\text{min}}$) and a maximum ($T_{\text{max}}$) temperature. For our calculations we have kept $T_{\text{max}}$ fixed at 4000 K, since gas at temperatures larger than this value is not expected to contribute to the emission of the observed pure rotational lines. $T_{\text{min}}$ was instead assumed to be equal, in each position, to the minimum temperature probed by the observed lines. This $T_{\text{min}}$ is taken as the excitation temperature giving rise to the observed ratio of the S(0) and S(1) column densities, assuming a Boltzman distribution. The $T_{\text{min}}$ value ranges between $\sim 150$ and 400 K.

We found that the approach of a variable $T_{\text{min}}$ always produces fits with a better $\chi^2$ than assuming a fixed low value in all positions. We also assume the gas is in LTE conditions. Critical densities of rotational lines from S(0) to S(7) range between 4.9 cm$^{-3}$ (S(0)) and 4.4 $\times$ 10$^5$ cm$^{-3}$ (S(7)) at $T = 1000$ K assuming only H$_2$ collisions (Le Bourlot et al. 1999): critical densities decrease if collisions with H and He are not negligible. Deviations from LTE can therefore be expected only for the high-$J$ S(6) and S(7) transitions: the signal-to-noise ratio (S/N) of these transitions in the individual pixels is however not high enough to disentangle, in the rotational diagrams, NLTE effects from the effects caused by the variations of the other considered parameters. In particular, as also discussed in N09, there is a certain degree of degeneracy in the density and the $\beta$ parameter of the temperature power law in an NLTE treatment that we are not able to remove in the analysis of the individual pixels. This issue will be further discussed in Section 3.2. An additional parameter of our fit is the OPR value. It is indeed recognized that the 0–0 H$_2$ lines are often far from being in OPR equilibrium, an effect that in a rotational diagram is evidenced by a characteristic zigzag behavior in which column densities of lines with even-$J$ lie systematically above those of odd-$J$ lines.

In order not to introduce too many parameters, we assume a single OPR value as a free parameter for the fit. In reality, the OPR value is temperature dependent (e.g., N09 and Section 3.2), and therefore the high-$J$ lines might present an OPR value closer to equilibrium than the low-$J$ transitions. Our fit therefore gives only a value averaged over the temperature range probed by the lines considered (i.e., $\sim 200$–1500 K).

In summary, we have varied only three parameters, namely the total H$_2$ column density $N$(H$_2$), the OPR, and the temperature power-law index $\beta$, in order to obtain the best model fit through a $\chi^2$ minimization procedure and assuming a 20% flux uncertainty for all the lines. The fit was performed only in those pixels where at least four lines with an S/N larger than 3 have been detected. Before performing the fit, the line column densities were corrected for extinction assuming $A_v = 2$ (Caratti o Garatti et al. 2006) and adopting the Rieke & Lebofsky (1985) extinction law. At the considered wavelengths, variations of $A_v$ of the order of 1–2 mag do not affect any of the derived results.

Figure 3 shows the derived map of the H$_2$ column density, while in Figures 4 and 5 maps of the OPR and $\beta$ are displayed together with temperature maps relative to the “cold” and “warm” components ($T_{\text{cold}}$ and $T_{\text{warm}}$), i.e., the temperature derived from linearly fitting the S(0)–S(1)–S(2) and S(5)–S(6)–S(7) lines, once corrected for the derived OPR value. In Figure 6, we also show the individual excitation diagrams for selected positions along the flow, obtained from intensities measured in a 20$''$ FWHM Gaussian aperture centered toward emission peaks (Table 1). Values of the fitted parameters in these positions are reported in Table 2. In addition to $T_{\text{cold}}$ and $T_{\text{warm}}$, we also give in this table the values of the average temperature in each knot, derived through a linear fit through all the H$_2$ lines ($T_{\text{med}}$).
**Figure 4.** As in Figure 3 for the map of the OPR. (A color version of this figure is available in the online journal.)

**Figure 5.** Maps of the fitted temperature power-law spectral index $\beta$ (a), and of the “cold” and “warm” temperature components, derived from a linear fit through the OPR corrected S(0)–S(1)–S(2) lines and S(5)–S(6)–S(7) lines, respectively. Contours of the intensity of the S(5) and S(1) lines are superimposed on the $T_{\text{warm}}$ and $T_{\text{cold}}$ images, respectively. (A color version of this figure is available in the online journal.)

**Figure 6.** $\text{H}_2$ rotational diagrams obtained at the offset positions indicated in each panel. The filled circles correspond to the observations while the solid line is the best LTE fit obtained in each position. The parameters of each fit are summarized in Table 2. (A color version of this figure is available in the online journal.)
The maps show significant variations in the inferred parameters along the outflow. The H$_2$ column density ranges between $5 \times 10^{20}$ and $3 \times 10^{20}$ cm$^{-2}$. The region at the highest column density is located toward the B1 molecular bullet (see Figure 2).5 This is consistent with the higher column density of CO found in B1 with respect to other positions in the blueshifted lobe (Bachiller & Perez-Gutierrez 1997), and might suggest that this is a zone where the outflowing gas is compressed due to the impact with a region of higher density (Nisini et al. 2007). Toward the NW, redshifted outflow, the column density has a more uniform distribution, with a plateau at $\sim 10^{20}$ cm$^{-2}$ that follows the H$_2$ intensity distribution. The $N$(H$_2$) decreases at the apex of the redshifted outflow, with a value slightly below $10^{20}$ cm$^{-2}$ at the position of the D near-IR knot.

$T_{\text{cold}}$ ranges between $\sim 250$ and 550 K. The highest values are found at the tip of the northern outflow lobe, while local maxima correspond to the positions of line intensity peaks. $T_{\text{warm}}$ ranges between $\sim 1000$ and 1500 K. In this case the highest values are in the southern lobe, at the position of the A NIR knot. As a general trend, the $T_{\text{warm}}$ value decreases going from the southern to the northern peaks of emission, with the minimum value at the position of the D NIR knot.

$\beta$ values range between $\sim 4$ and 4.5 in the blueshifted lobe while they are larger in the redshifted lobe, with maximum values of $\sim 5.5$ at the tip of the flow. Due to the degeneracy between $\beta$ and density discussed in the previous section, these values can be considered as upper limits because of our assumption of LTE conditions. Neufeld & Yuan (2008) have discussed the $\beta$ index expectations in bow shock excitation. A $\beta$ index of $\sim 3.8$ is expected in paraboloid bow shocks having a velocity at the bow apex high enough to dissociate H$_2$, in which case the temperature distribution extends to the maximum allowed temperature. Slower shocks that are not able to attain the maximum temperature produce steeper temperature distributions, i.e., with values of $\beta$ greater than 3.8. This is consistent with our findings: low values of $\beta$ (of the order of 4) are found in the blueshifted lobe: here, evidence of H$_2$ dissociation is given by the detection of atomic lines (i.e., [Sii], [Feii], and [Si]) in the IRS spectrum. In the redshifted lobe, where values of $\beta$ larger than 4 are derived in the LTE assumption, no atomic emission is detected and the $T_{\text{warm}}$

values are lower than those measured in the blueshifted lobe, indicating a maximum temperature lower than in the blueshifted flow.

The OPR varies significantly along the outflow, spanning from $\sim 0.6$ to 2.8. Hence it is always below the equilibrium value of 3. Although a one-to-one correlation between temperature and OPR cannot be discerned, some trends can be inferred from inspection of Figure 5. In general, the OPR minima are observed in plateau regions between two consecutive intensity peaks, where the cold temperature also has its lowest values. At variance with this trend, the emission filaments delineating the outflow cavity within $\pm 20^\circ$ from the millimeter source, where the cold temperature reaches a minimum value of $\sim 250$ K, show rather high values of the OPR, $\sim 2.4$–2.8. This might suggest that this region has experienced an older shock event that has raised the OPR, though not to the equilibrium value, and where the gas had time to cool at a temperature close to the pre-shock gas temperature. On the other hand, at the apex of both the blueshifted and redshifted lobes, where the cold temperatures are relatively high (i.e., 500–550 K), the OPR is rather low, 1.5–2.0. Evidence of regions of low OPR and high temperatures at the outflow tips has been already given in other flows (Neufeld et al. 2006; Maret et al. 2009). It has been suggested that these represent zones subject to recent shocks where the OPR has not had time yet to reach the equilibrium value.

### 3.2. NLTE Analysis: Constraints on H and H$_2$ Particle Density

Additional constraints on the physical conditions responsible for the H$_2$ excitation are provided by combining the emission of the mid-IR H$_2$ pure-rotational lines from the ground vibrational level with the emission from near-IR ro-vibrational lines. It can be seen from Figure 2 that the 2.12 $\mu$m emission follows quite closely the emission of the 0–0 lines at higher $J$. In addition to the 2.12 $\mu$m data presented in Figure 2, we have also considered the NIR long-slit spectra obtained on the A and C NIR knots by Caratti o Garatti et al. (2006). These knots, at the spatial resolution of the NIR observations (i.e., $\sim 0.8$) are separated in several different sub-structures that have been individually investigated with the long-slit spectroscopic observations. For our analysis we have considered the data obtained on the brightest of the sub-structures, that coincide, in position, with peaks of the 1–0 S(1) line.

In order to inter-calibrate in flux the Spitzer data with these NIR long-slit data, obtained with a slit width of 0.5 arcsec, we have proceeded as follows: we first convolved the 2.12 $\mu$m image at the resolution of the Spitzer images and then performed photometry on the A and C peaks positions with a $20^\prime$ diameter Gaussian aperture, i.e., with the same aperture adopted for the brightness given in Table 1. We have then scaled the fluxes of the individual lines given in Caratti o Garatti et al. (2006) in order to match the 2.12 $\mu$m flux gathered in the slit with that measured by the image photometry. In doing this, we assumed that the average excitation conditions within the $20^\prime$ aperture are not very different from those of the A–C peaks. This assumption is observationally supported by the fact that the ratios of different H$_2$ NIR lines do not change significantly (i.e., less than 20%) in the A–C knot substructures separately investigated in Caratti o Garatti et al. (2006). We have considered only those lines detected with S/N larger than 5; in practice this means considering lines from the first four and three vibrational levels for knots A and C, respectively. The excitation diagrams obtained by combining the Spitzer and NIR data for these two knots are displayed in Figure 8.
In order to model together the 0–0 lines and the near-IR ro-vibrational lines, we have implemented two modifications to the approach adopted previously. First of all, the NIR lines probe gas at temperatures higher than the pure rotational lines, of few thousands of K, at which values it is expected that the OPR has already reached equilibrium. Thus, the ortho-para conversion time as a function of temperature needs to be included in the fitting procedure, since lines excited at different temperatures have different OPRs. We have here adopted the approach of N09 and used an analytical expression for the OPR as a function of the temperature, considering a gas that had an initial value of the OPR, OPR0, and has been heated to a temperature T for a time τ. Assuming that the para-to-ortho conversion occurs through reactive collisions with atomic hydrogen, we have

\[
\frac{\text{OPR}(\tau)}{1 + \text{OPR}(\tau)} = \frac{\text{OPR}_0}{1 + \text{OPR}_0} e^{-n_\text{H}k_\text{H}} = \frac{\text{OPR}_{\text{LTE}}}{1 + \text{OPR}_{\text{LTE}}} (1 - e^{-n_\text{H}k_\text{H}}). \quad (1)
\]

In this expression, \( n_\text{H} \) is the number density of atomic hydrogen and \( \text{OPR}_{\text{LTE}} \) is the OPR equilibrium value. The parameter \( k_\text{H} \) is given by \( 8 \times 10^{-11} \exp(-3900/T) \) \( \text{cm}^3 \text{s}^{-1} \), and for OPR conversion, \( k_\text{OP} \approx k_\text{p} \) (Schofield 1967). Thus, the dependence of the OPR on the temperature is implicitly given by the dependence on \( T \) of the \( k \) coefficient. The inclusion of a function of OPR on \( T \) introduces one additional parameter to our fit: while we have previously considered only the average OPR of the 0–0 lines, we will fit here the initial OPR0 value and the coefficient \( \beta = n_\text{H} \tau \).

The second important change that we have introduced with respect to the previous fitting procedure is to include an NLTE treatment of the H2 level column densities. In fact, the critical densities of the NIR lines are much higher than those of the pure rotational lines (see Le Bourlot et al. 1999). For example, \( n_{\text{crit}} \) of the 1–0 S(1) 2.12 \( \mu \text{m} \) line is \( 10^5 \text{ cm}^{-3} \) assuming only collisions with H2 and \( T = 2000 \text{ K} \). Therefore, the previously adopted LTE approximation might not be valid when combining lines from different vibrational levels. This is illustrated in Figure 7, where we plot the results obtained by varying the H2 density between \( 10^5 \) and \( 10^9 \text{ cm}^{-3} \), while keeping the other model parameters fixed. The observed column densities in the A position are displayed for comparison. For the NLTE statistical equilibrium computation we have adopted the H2 collisional rate coefficients given by Le Bourlot et al. (1999). This figure demonstrates the sensitivity of the relative ratios between 0–0 and 1–0 transitions to density variations. For example, in this particular case, the ratio \( N(\text{H}_2)_{0\rightarrow 0}/N(\text{H}_2)_{1\rightarrow 0} \) is 64.6 at \( n(\text{H}_2) = 10^4 \text{ cm}^{-3} \) and 1.9 at \( n(\text{H}_2) > 10^6 \text{ cm}^{-3} \). The figure also shows that the observational points display only a small misalignment in column densities between the 0–0 lines and the 1–0 lines, already indicating that the ro-vibrational lines are close to LTE conditions at high density.

In Figure 8, we show the final best-fit models for the combined mid- and near-IR column densities in the A and C positions. As anticipated, the derived \( n(\text{H}_2) \) densities are large, of the order of \( 10^5 \) and \( 6 \times 10^9 \text{ cm}^{-3} \) for the A and C positions, respectively. The two positions indeed show very similar excitation conditions:

\[ \beta = 4 \]

\[ \text{N}(\text{H}_2) = 2 \times 10^{10} \text{ cm}^{-2} \]

\[ (\alpha/\beta_\text{H}) = 0.6 \]

Figure 7. H2 rotational diagram showing the results of the NLTE model at different H2 densities for the Spitzer-observed rotational lines and three bright NIR lines at excitation temperatures between 6000 and 8000 K. The model assumes a slab where the temperature decreases as a power law with index \( \beta \) and where the OPR varies as a function of temperature. The gas is assumed fully molecular (H2/H = 0). Filled squares correspond to the observations in a 20” aperture centered toward the knot A in the SE lobe (see Figure 1). Different symbols indicate the model results at different densities: the other parameters are indicated in the figure and are kept fixed. It should be noted how the near-IR lines are much more sensitive to density variations than the pure rotational lines, due to their different critical densities.

(A color version of this figure is available in the online journal.)

only the column density is a factor of 3 smaller in knot C. Hence, we conclude that the lack of detection of rotational lines with \( v > 3 \) in knot C, in contrast to knot A (Caratti o Garatti et al. 2006), is purely due to a smaller number of emitting molecules along the line of sight and not to different excitation conditions. The derived H2 densities are much higher than previous estimates based on other tracers. Nisini et al. (2007) derive a density of \( 4 \times 10^5 \text{ cm}^{-3} \) at the position of knot A from multi-line SiO observations, thus more than an order of magnitude smaller than those inferred from our analysis. The high-J CO lines observed along the blueshifted lobe of L1157 by Hirano & Taniguchi (2001), indicate a density even smaller, of the order of \( 4 \times 10^4 \text{ cm}^{-3} \). SiO is synthesized and excited in a post-shock cooling zone where the maximum compression is reached; therefore, it should trace post-shock regions at densities higher than H2 (e.g., Gusdorf et al. 2008). One possibility at the origin of the discrepancy is our assumption of collisions with only H2 molecules, and thus of a negligible abundance of H. This can be considered roughly true in the case of non-dissociative C-shocks, where H atoms are produced primarily in the chemical reactions that form H2O from O and H2, with an abundance \( n(\text{H})/n(\text{H}_2+\text{H}) \sim 10^{-3} \) (e.g., Kaufmann & Neufeld 1996). However, if the shock is partially dissociative, the abundance of H can increase considerably and collisions with atomic hydrogen cannot be neglected, in view of its large efficiency in the H2 excitation. This situation cannot be excluded at least for the knot A, where atomic emission from [Feii] and [Si] has been detected in our Spitzer observations. Since we cannot introduce \( n(\text{H}) \) as an additional independent parameter of our fit, we have fixed \( n(\text{H}_2) \) at the value derived from SiO observations \( 4 \times 10^5 \text{ cm}^{-3} \); Nisini et al. (2007) and varied the H/H2 abundance ratio (see Figure 9). The best fit is in this case obtained with a ratio H/H2 = 0.3; this indicates that our observational data are consistent with previous H2 density determinations only if a large fraction of the gas is in atomic form.

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6 The rate coefficients for collisions with ortho- and para-H2, H1, and He, computed in Le Bourlot et al. (1999) are available at the Web site:
http://ccp7.dur.ac.uk/cooling_by_h2/
Turning back to the inferred OPR variations with temperature, our fit implies that the OPR in the cold gas component at $T = 300$ K is significantly below the equilibrium value, while the value of OPR $= 3$ is reached in the hot gas at $T = 2000$ K traced by the NIR lines. The parameter $K = n(H)\beta$ is constrained to be $\sim 10^6$ and $10^7$ yr cm$^{-3}$ for knots A and C, respectively. We can also estimate the time needed for the gas to reach this distribution of OPR, from the limits on the atomic hydrogen abundance previously discussed. Our data implies a high value of the $n(H)$ density: a minimum value of $n(H) \sim 0.6-1 \times 10^4$ cm$^{-3}$ (for knots C and A, respectively) is given if we assume $H_2/H$ $\sim 10^{-3}$ (and thus $n(H_2) \sim 5 \times 10^7$ cm$^{-3}$ given by our fit), while a maximum value of $\sim 10^5$ cm$^{-3}$ is derived from the fit where $n(H_2)$ is kept equal to $4 \times 10^3$ cm$^{-3}$. The high abundance of atomic H ensures that conversion of para- to ortho-$H_2$ proceeds very rapidly; the fitted values of the $K$ parameter indeed imply that the observed range of OPR as a function of temperature have been attained in a timescale between 100 and 1000 yr for both the knots.

Finally, given the column density and particle density discussed above, we can estimate the $H_2$ cooling length ($L \sim N(H_2)/n(H_2)$). If we consider the case of $n(H_2) \sim 10^7$ cm$^{-3}$ and negligible $n(H)$, we have $L \sim 10^{13}$ cm while a length of $\sim 10^{15}$ cm is inferred in the case of $n(H_2) \sim 4 \times 10^5$ cm$^{-3}$. All the parameters derived from the above analysis are summarized in Table 3 and they will be discussed in the following section in the framework of different shock models.

### 4. DISCUSSION

#### 4.1. Shock Conditions Giving Rise to the $H_2$ Emission

The copious $H_2$ emission at low excitation observed along the L1157 outflow indicates that the interaction of the flow with the ambient medium occurs prevalently through non-dissociative shocks. Both the Spitzer-IRS maps of N09 and the NIR narrow band images of Caratti o Garatti et al. (2006) show that significant gas dissociation in L1157 occurs only at the A peak, where both mid-IR lines from [Fe ii], [S ii], and [S i], and weak [Fe ii] at 1.64 $\mu$m have been detected. Weaker [S i] $25 \mu$m and [Fe ii] $26 \mu$m emission have also been detected on the C spot, but overall the atomic transitions give a negligible contribution to the total gas cooling, as pointed out in N09. These considerations suggest that most of the shocks along the outflow occur at speeds below $\sim 40$ km s$^{-1}$, as this is the velocity limit above which $H_2$ is expected to be dissociated. The knot A is the only one showing a clear bow shock structure. Here, the velocity at the bow apex is probably high, causing $H_2$ dissociation and atomic line excitation, consistent with the fitted temperature power law $\beta \sim -4$, as discussed in Section 3.1, while the bulk of the $H_2$ emission comes from shocks at lower velocities originating in the bow wings.

Constraints on the shock velocity that gives rise to the molecular emission in L1157 have been already given in previous works. The submillimeter SiO emission and abundances,
measured in different outflow spots, suggest shock velocities of the order of 20–30 km s\(^{-1}\) (Nisini et al. 2007). The comparison of SiO and H\(_2\) emission against detailed shock models performed by Gusdorf et al. (2008) confirm a similar range of velocities in the NIR-A knot, although the authors could not find a unique shock model that well represents both the emissions.

Cabrit et al. (1999) found that the column density of the mid-IR H\(_2\) emission lines, from S(2) to S(8), observed by ISO-ISOCAM was consistent either with C-shocks having velocities of \(\sim 25\) km s\(^{-1}\) or with J-shocks at a lower velocity of the order of \(\sim 10\) km s\(^{-1}\). Gusdorf et al. (2008), however, conclude that stationary shock models, either of C- or J-type, are not able to reproduce the observed rotational diagram on the NIR-A position, constructed combining ISOCAM data and NIR vibrational lines emission. A better fit was obtained by these authors considering non-stationary shock models, which have developed a magnetic precursor but which retain a J-type discontinuity (the so-called CJ shocks, Flower et al. 2003).

Similar conclusions, but on a different outflow, have been reached by Giannini et al. (2006) who studied the H\(_2\) mid- and near-IR emission in HH54: in general, steady-state C- and J-type shocks fail to reproduce simultaneously the column densities of both the ro-vibrational and \(v = 0\), pure-rotational H\(_2\) levels.

A different way to look at the issue of the prevailing shock conditions in the observed regions is to compare the set of physical parameters that we have inferred from our analysis to those expected from different shocks. With this aim, we summarize in Table 3 the physical properties derived on the A and C H\(_2\) knots. In addition to the parameters derived from the NLTE analysis reported in Section 2, namely H\(_2\) post-shock density, H\(_2\)/H\(_2\) fraction, initial OPR, cooling length, and time, the table reports also the average values of OPR and rotational temperature, as they are measured from a simple linear fit of the rotational diagrams presented in Figure 6.

As mentioned in Section 3.2, the high fraction of atomic hydrogen inferred by our analysis rules out excitation in a pure C-shock. In fact, dissociation in C-shocks is always too low to have an H/H\(_2\) ratio higher than \(5 \times 10^{-3}\), irrespective of the shock velocity and magnetic field strength (Kaufman & Neufeld 1996; Wilgenbus et al. 2000). C-shocks are not consistent with the derived parameters even if we consider the model fit with the high H\(_2\) post-shock density of the order of \(10^5\) cm\(^{-3}\) and negligible atomic hydrogen: in this case, we derive an emission length of \(10^{13}\) cm, which is much lower than the cooling length expected in C-shocks, which, although decreasing with the pre-shock density, is never less than \(10^{15}\) cm (Neufeld et al. 2006).

Stationary J-shock models better reproduce some of our derived parameters. For example, in J-type shocks the fraction of hydrogen in the post-shocked gas can reach the values of 0.1–0.3 we have inferred, provided that the shock velocity is larger than \(\sim 20\) km s\(^{-1}\). In general, a reasonable agreement with the inferred post-shock density and H/H\(_2\) ratio is achieved with models having \(v_s = 20–25\) km s\(^{-1}\) and pre-shock densities of \(10^5\) cm\(^{-3}\) (Wilgenbus et al. 2000). Such models predict a shock flow time of the order of 100 yr or less, which is also in agreement with the value estimated in our analysis at least in knot A. In such models, however, the cooling length is an order of magnitude smaller than the inferred value of \(\sim 10^{15}\) cm. In addition, the gas temperature remains high for most of the post-shocked region: the average rotational temperature of the \(v = 0\) vibrational level is predicted to be, according to the Wilgenbus et al. (2000) grid of models, always about 1600 K or larger, as compared with the value of about 800–900 K inferred from observations. The consequence of the above inconsistencies is that J-type shocks tend to underestimate the column densities of the lowest H\(_2\) rotational levels in L1157, an effect already pointed out by Gusdorf et al. (2008).

As mentioned before, Gusdorf et al. (2008) conclude that the H\(_2\) pure rotational emission in L1157 is better fitted with a non-stationary C+J shock model with either \(v_s\) between 20 and 25 km s\(^{-1}\) and pre-shock densities \(n_H = 10^4\) cm\(^{-3}\), or with \(v_s \sim 15\) km s\(^{-1}\) and higher pre-shock densities of \(n_H = 10^5\) cm\(^{-3}\). Such models, however, still underestimate the column densities of the near-IR transitions: the post-shocked H\(_2\) gas density remains lower than the NIR transitions critical density and the atomic hydrogen produced from H\(_2\) dissociation is not high enough to populate the vibrational levels to equilibrium conditions.

The difficulty of finding a suitable single model that reproduce the derived physical conditions is likely related to possible geometrical effects and to the fact that multiple shocks with different velocities might be present along the line of sight. It would be indeed interesting to explore whether bow shock models might be able to predict the averaged physical characteristics along the line of sight that we infer from our analysis.

4.2. Flow Energetics

H\(_2\) emission represents one of the main contributors to the energy radiated away in shocks along outflows from very young stars. Kaufman & Neufeld (1996) predicted that between 40% and 70% of the total shock luminosity is emitted in H\(_2\) lines for shocks with pre-shock density lower than \(10^3\) cm\(^{-3}\) and shock velocities larger than \(20\) km s\(^{-1}\), the other main contributions being in CO and H\(_2\)O rotational emission. This has also been observationally tested by Giannini et al. (2001) who measured the relative contribution of the different species to the outflow cooling in a sample of class 0 objects observed with ISO–LWS (Long Wavelength Spectrometer).

We will discuss here the role of the H\(_2\) cooling in the global radiated energy of the L1157 outflow. From the best-fit model obtained for the knots A and C, we have derived the total, extinction corrected, H\(_2\) luminosity by integrating over all the ro-vibrational transitions considered by our model. \(L_{H_2}\) is found to be \(8.4 \times 10^{-2}\) and \(3.7 \times 10^{-2}\) \(L_\odot\) for the A and C knots, respectively. Out of this total luminosity, the contribution of the rotational lines is only \(5.6 \times 10^{-2}\) (A) and \(2.7 \times 10^{-2}\) (C) \(L_\odot\), which means that in both cases they represent about 70% of the total H\(_2\) luminosity.

N09 have found that the total luminosity of the H\(_2\) rotational lines from S(0) to S(7), integrated over the entire L1157 outflow, amount to 0.15 \(L_\odot\). If we take into account an additional 30% of contribution from the \(v > 0\) vibrational levels, we estimate a total H\(_2\) luminosity of 0.21 \(L_\odot\). This is 30% larger than the total H\(_2\) luminosity estimated by Caratti o Garatti et al. (2006) in this outflow, assuming a single component gas at temperature between 2000 and 3000 K that fit the NIR H\(_2\) lines.

If we separately compute the H\(_2\) luminosity in the two outflow lobes, we derive \(L_{H_2} = 8.5 \times 10^{-2}\) \(L_\odot\) in the blueshifted lobe and \(1.3 \times 10^{-1}\) \(L_\odot\) in the redshifted lobe. Comparing these numbers with those derived in the individual A and C knots, we note that the A knot alone contributes to most of the H\(_2\) luminosity in the blueshifted lobe. In contrast, the H\(_2\) luminosity of the redshifted lobe is distributed among several peaks of similar values. This might suggest that most of the energy carried out by the blueshifted jet is released when the leading bow shock
encounters a density enhancement at the position of the A knot. On the other hand, the redshifted gas flows more freely without large density discontinuities, and the corresponding shocks are internal bow shocks, all with similar luminosities.

The integrated luminosity radiated by CO, H$_2$O, and OI in L1157 has been estimated, through ISO and recent Herschel observations, as $\sim 0.2 \, L_{\odot}$ (Giannini et al. 2001; Nisini et al. 2010), which means that H$_2$ alone contributes about 50% of the total luminosity radiated by the outflow. Including all contributions, the total shock cooling along the L1157 outflow amounts to about 0.4 $L_{\odot}$, i.e., $L_{\text{cool}}/L_{\text{bol}} \sim 5 \times 10^{-2}$, assuming $L_{\text{bol}} = 8.4 \, L_{\odot}$ for L1157 mm (Froebrich 2005). This ratio is consistent with the range of values derived from other class 0 sources from ISO observations (Nisini et al. 2002).

The total kinetic energy of the L1157 molecular outflow estimated by Bachiller et al. (2001) amounts to 0.2 $L_{\odot}$ without any correction for the outflow inclination angle, or to 1.2 $L_{\odot}$ if an inclination angle of 80$^\circ$ is assumed. Considering that the derivation of the $L_{\text{km}}$ value has normally an uncertainty of a factor of 5 (Downes & Cabrit 2007), we conclude that the mechanical energy flux into the shock, estimated as $L_{\text{cool}}$, is comparable to the kinetic energy of the swept-out outflow and thus that the shocks giving rise to the H$_2$ emission have enough power to accelerate the molecular outflow.

The total shock cooling derived above can also be used to infer the momentum flux through the shock, i.e., $P = 2L_{\text{cool}}/v_r$, where $v_r$ is the shock velocity that we can assume, on the basis of the discussion in the previous section, to be of the order of 20 km s$^{-1}$. Computing the momentum flux separately for the blueshifted and redshifted outflow lobe, we derive $P_{\text{red}} \sim 1.7 \times 10^{-4}$ and $P_{\text{blue}} \sim 1.1 \times 10^{-4}$ $M_{\odot}$ yr$^{-1}$ km s$^{-1}$. In this calculation, we have assumed that the contribution from cooling species different from H$_2$, as estimated by ISO and Herschel, is distributed among the two lobes in proportion to the H$_2$ luminosity. If we assume that the molecular outflow is accelerated at the shock front through momentum conservation, then the above-derived momentum flux should result comparable to the thrust of the outflow, derived from the mass, velocity, and age measured through CO observations. The momentum flux measured in this way by Bachiller et al. (2001) is $1.1 \times 10^{-4}$ and $2 \times 10^{-4}$ $M_{\odot}$ yr$^{-1}$ km s$^{-1}$ in the blueshifted and redshifted lobes, respectively, i.e., comparable to our derived values. It is interesting to note that the $P$ determination from the shock luminosity confirms the asymmetry between the momentum fluxes derived in two lobes. As shown by Bachiller et al. (2001), the L1157 redshifted lobe has a 30% smaller mass with respect to the blueshifted lobe, but a higher momentum flux due to the larger flow velocity. The northern redshifted lobe is in fact more extended than the southern lobe; however, given the higher velocity of the redshifted gas, the mean kinematical ages of the two lobes are very similar.

5. CONCLUSIONS

We have analyzed the H$_2$ pure rotational line emission, from S(0) to S(7), along the outflow driven by the L1157 mm protostar, mapped with the Spitzer-IRS instrument. The data have been analyzed assuming a gas temperature stratification where the H$_2$ column density varies as $T^{-\beta}$ and two-dimensional maps of the H$_2$ column density, OPR, and temperature spectral index $\beta$ have been constructed. Further constraints on the physical conditions of the shocked gas have been derived in two bright emission knots by combining the Spitzer observations with near-IR data of H$_2$ ro-vibrational emission. Finally, the global H$_2$-radiated energy of the outflow has been discussed in comparison with the energy budget of the associated CO outflow.

The main conclusions derived by our analysis are the following.

1. H$_2$ transitions with $J_{\text{lower}} \leq 2$ follow the morphology of the CO molecular outflow, with peaks correlated with individual CO clumps and more diffuse emission that delineates the CO cavities created by the precessing jet. Lines with higher $J$ are localized on the shocked peaks, presenting a morphology similar to that of the H$_2$ 2.12 $\mu$m ro-vibrational emission.

2. Significant variations of the derived parameters are observed along the flow. The H$_2$ column density ranges between $5 \times 10^{19}$ and $3 \times 10^{20}$ cm$^{-2}$; the highest values are found in the blueshifted lobe, suggesting that here the outflowing gas is compressed due to the impact with a high-density region. Gas components in a wide range of temperature values, from $\sim 250$ to $\sim 1500$ K, contribute to the H$_2$ emission along individual lines of sight. The largest range of temperature variations is derived toward the intensity peaks closer to the driving source, while a more uniform temperature distribution, with $T$ between 400 and 1000 K, is found at the tip of the northern outflow lobe.

3. The OPR is in general lower than the equilibrium value at high temperatures and spans a range from $\sim 0.6$ to 2.8, with the lowest values found in low temperature plateau regions between consecutive intensity peaks. As in previous studies, we also found the presence of regions at low OPR (1.5–1.8) but with relatively high temperatures. These might represent zones subject to recent shocks where the OPR has not had time yet to reach the equilibrium value.

4. Additional shock parameters have been derived in the two bright near-IR knots A and C, located in the blueshifted and redshifted outflow lobes, where the mid- and near-IR H$_2$ data have been combined. The ratio between mid- and near-IR lines is very sensitive to the molecular plus atomic hydrogen particle density. A high abundance of atomic hydrogen ($H/\text{H}_2 \sim 0.1–0.3$) is implied by the the observed H$_2$ column densities if we assume $n(\text{H}_2)$ values as derived by independent mm observations. With this assumption, the cooling lengths of the shock result of the order of $7 \times 10^{14}$ and $10^{15}$ cm for the A and C knots, respectively. The distribution of OPR values as a function of temperature and the derived abundance of atomic hydrogen, implies that the shock passing time is of the order of 100 yr for knot A and 1000 yr for knot C, given the assumption that the para-to-ortho conversion occurs through reactive collisions with atomic hydrogen. We find that planar shock models, either of C- or J-type, are not able to consistently reproduce all the physical parameters derived from our analysis of the H$_2$ emission.

5. Globally, H$_2$ emission contributes to about 50% of the total shock radiated energy in the L1157 outflow. We find that the momentum flux through the shocks derived from the radiated luminosity is comparable to the thrust of the associated molecular outflow, supporting a scenario where the working surface of the shocks drives the molecular outflow.

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REFERENCES

Arce, H. G., Santiago-García, J., Jørgensen, J. K., Tafalla, M., & Bachiller, R. 2008, ApJ, 681, L21
Bachiller, R., & Perez Gutierrez, M. 1997, ApJ, 487, L93
Bachiller, R., Pérez Gutiérrez, M., Kumar, M. S. N., & Tafalla, M. 2001, A&A, 372, 899
Benedettini, M., Viti, S., Codella, C., Bachiller, R., Gueth, F., Beltrán, M. T., Dutrey, A., & Guilloteau, S. 2007, MNRAS, 381, 1127
Cabrit, S., et al. 1999, in ESA-SP 427, The Universe as Seen by ISO, ed. P. Cox & M. F. Kessler (Noordwijk: ESA), 449
Caratti o Garatti, A., Giannini, T., Nisini, B., & Lorenzetti, D. 2006, A&A, 449, 1077
Codella, C., et al. 2009, A&A, 507, L25
Codella, C., et al. 2010, A&A, 518, L112
Davis, C.J., & Eislöffel, J. 1995, A&A, 300, 851
Dionatos, O., Nisini, B., Cabrit, S., Kristensen, L., & Pineau Des Forêts, G. 2010, A&A, in press (arXiv:1006.0821)
Downes, T. P., & Cabrit, S. 2007, A&A, 471, 873
Eislöffel, J., Smith, M. D., & Davis, C. J. 2000, A&A, 359, 1147
Flower, D. R., Le Bourlot, J., Pineau des Forêts, G., & Cabrit, S. 2003, MNRAS, 341, 70
Froebrich, D. 2005, ApJS, 156, 169
Giannini, T., McCoey, C., Caratti o Garatti, A., Nisini, B., Lorenzetti, D., & Flower, D. R. 2004, A&A, 419, 999
Giannini, T., McCoey, C., Nisini, B., Cabrit, S., Caratti o Garatti, A., Calzoletti, L., & Flower, D. R. 2006, A&A, 459, 821
Giannini, T., Nisini, B., & Lorenzetti, D. 2001, ApJ, 555, 40
Gueth, F., Guilloteau, S., & Bachiller, R. 1996, A&A, 307, 891
Gueth, F., Guilloteau, S., & Bachiller, R. 1998, A&A, 333, 287
Gusdorf, A., Pineau Des Forêts, G., Cabrit, S., & Flower, D. R. 2008, A&A, 490, 695
Hirano, N., & Taniguchi, Y. 2001, ApJ, 550, L219
Houck, J. R., et al. 2004, ApJS, 154, 18
Kauffman, M. J., & Neufeld, D. A. 1996, ApJ, 456, 611
Le Bourlot, J., Pineau des Forêts, G., & Flower, D. R. 1999, MNRAS, 305, 802
Lefloch, B., Cernicharo, J., Cabrit, S., Noriega-Crespo, A., Moro-Martín, A., & Cesarsky, D. 2003, A&A, 590, L41
Lefloch, B., et al. 2010, A&A, 518, L113
Looney, L. W., Tobin, J. J., & Kwon, W. 2007, ApJ, 670, L131
Maret, S., et al. 2009, ApJ, 698, 1244
Molinari, S., et al. 2000, ApJ, 538, 698
Neufeld, D. A., Melnick, G. J., & Harwit, M. 1998, ApJ, 506, L75
Neufeld, D. A., & Yuan, Y. 2008, ApJ, 678, 974
Neufeld, D. A., et al. 2006, ApJ, 649, 816
Neufeld, D. A., et al. 2009, ApJ, 706, 170 (N09)
Nisini, B., Benedettini, M., Giannini, T., Codella, C., Lorenzetti, D., di Giorgio, A. M., & Richer, J. S. 2000, A&A, 360, 297
Nisini, B., Codella, C., Giannini, T., Santiago Garcia, J., Richer, J. S., Bachiller, R., & Tafalla, M. 2007, A&A, 462, 163
Nisini, B., Giannini, T., & Lorenzetti, D. 2002, ApJ, 574, 246
Nisini, B., et al. 2010, A&A, 518, L120
Ricke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Rodríguez-Fernández, N. J., Tafalla, M., Gueth, F., & Bachiller, R. 2010, A&A, 516, A98
Schloerb, K. 1967, Planet. Space Sci., 15, 643
Wilgenbus, D., Cabrit, S., Pineau des Forêts, G., & Flower, D. R. 2000, A&A, 356, 1010
Zhang, Q., Ho, P. T. P., & Wright, M. C. H. 2000, AJ, 119, 1345