ATOMIC JETS FROM CLASS 0 SOURCES DETECTED BY SPITZER: THE CASE OF L1448-C

O. Dionatos$^1$, B. Nisini$^1$, R. Garcia Lopez$^1$, T. Giannini$^1$, C. J. Davis$^2$, M. D. Smith$^3$, T. P. Ray$^4$, and M. De Luca$^5$

$^1$INAF-Osservatorio Astronomico di Roma Via di Frascati 33, 00040, Monteporzio Catone, Italy; dionatos@oa-roma.inaf.it, nisini@oa-roma.inaf.it, gcassia@oa-roma.inaf.it
$^2$Joint Astronomy Centre, 660 North A‘ohoku Place, University Park Hilo, Hawaii 96720, USA; c.davis@jach.hawaii.edu
$^3$School of Physical Sciences, Ingram Building, The University of Kent, Canterbury CT2 7NH, UK; m.d.smith@kent.ac.uk
$^4$Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland; tr@cp.dias.ie
$^5$Indiana University Cyclotron Facility, 2401 N. Milo B. Sampson Lane 47408 Bloomington, IN, USA; delucama@indiana.edu

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ABSTRACT

We present Spitzer-IRS spectra obtained along the molecular jet from the Class 0 source L1448-C (or L1448-mm). Atomic lines from the fundamental transitions of [Fe ii], [Si ii], and [S i] have been detected showing, for the first time, the presence of an embedded atomic jet at low excitation. Pure rotational H$_2$ lines are also detected, and a decrease of the atomic/molecular emission ratio is observed within 1′ from the driving source. Additional ground-based spectra (UK Infrared Telescope/UIST) were obtained to further constrain the H$_2$ excitation along the jet axis and, combined with the 0–0 lines, have been compared with bow shock models. From the different line ratios, we find that the atomic gas is characterized by an electron density $n_e \sim 200$–1000 cm$^{-3}$, a temperature $T_e < 2500$ K, and an ionization fraction $\lesssim 10^{-2}$; the excitation conditions of the atomic jet are thus very different from those found in more evolved Class I and Class II jets. We also infer that only a fraction (0.05–0.2) of Fe and Si is in gaseous form, indicating that dust still plays a major role in the depletion of refractory elements. A comparison with the SiO abundance recently derived in the jet from an analysis of several SiO submillimeter transitions shows that the Si/SiO abundance ratio is $\sim 100$, and thus, that most of the silicon released from grains by sputtering and grain–grain collisions remains in atomic form. Finally, estimates of the atomic and molecular mass flux rates have been derived: values of the order of $\sim 10^{-6}$ and $\sim 10^{-7}$ $M_\odot$ yr$^{-1}$ are inferred from the [S i] 25 μm and H$_2$ line luminosities, respectively. A comparison with the momentum flux of the CO molecular outflow suggests that the detected atomic jet has the power to drive the large-scale outflow.

Key words: infrared: ISM – ISM: individual (L1448-C) – ISM: jets and outflows – ISM: lines and bands – stars: formation

Online-only material: color figures

1. INTRODUCTION

The process of mass accretion, leading to the formation of solar-type stars, is always associated with mass ejection in the form of collimated jets, which extend from a few astronomical unit (AU) up to parsecs away from the exciting source. According to the models (Königl & Pudritz 2000; Casse & Ferreira 2000), accretion and ejection are intimately related through the presence of a magnetized accretion disk: the jets carry away the excess angular momentum, so that part of the disk material can move toward the star. This paradigm of star formation is now being observationally tested in Class I and Class II objects through detailed optical and near-IR observations (Ray et al. 2007).

However, the characteristics of jets from these evolved young stellar objects (YSOs) are unlikely to be appropriate for those from protostars in earlier evolutionary phases, which are expected to propagate in a denser medium and be associated with more energetic mass ejection. In such unevolved objects, so-called Class 0 sources, the initial part of the jet is often detectable only at millimeter wavelengths in the form of a collimated, high-velocity molecular outflow (Gueth & Guilloteau 1999; Lee et al. 2007; Codella et al. 2007). Near-IR H$_2$ emission is always obscured by high extinction near the central engine and jet base, and instead traces hot gas excited further downstream in bow shocks near or at the jet apex. While it is usually assumed that the molecular jet represents the cold external layer of an embedded atomic jet, in principle the jet could be composed entirely of low excitation molecular gas and this needs to be tested observationally.

Millimeter interferometric observations of high-velocity molecular jets from Class 0 sources present characteristics very similar to the hot jets seen in T-Tauri or Class I YSOs, such as a very narrow ($< 2''$) width and a knotty structure resembling that of HH objects (Gueth & Guilloteau 1999; Cabrit et al. 2007). Submillimeter observations in CO and SiO show that such jets are dense, with peak values of $n$(H$_2$) $\sim 10^4$ cm$^{-3}$ (e.g., Nisini et al. 2007). Moreover, ISO-LWS observations suggest that they are also warm, with temperatures between 300 and 1500 K inferred from the copious high-J CO and H$_2$O emission (Giannini et al. 2001). Such a warm gas component may represent the bulk of the mass flux ejected by the protostar, and thus, energetically, may be the jet’s most important component. The very low LWS spatial resolution, however, has not permitted us to draw any conclusions about the detailed structure of this warm gas, giving only physical parameters averaged over the entire outflow.

Spitzer observations now allow us to investigate the properties of the warm gas component of the molecular jet through mid-IR atomic and molecular features probing low excitation gas at $T \sim 100$–2000 K and $n \sim 10^2$–$10^4$ cm$^{-3}$. The moderate IRS spatial resolution ($4''$$\sim 20''$) allows one to separate, in nearby sources, the inner jet region from the region where the jet is strongly interacting with the ambient medium through bow shocks.

In this study, we present results of an analysis performed on Spitzer-IRS spectra of the jet from the Class 0 source
L1448-C (or L1448-mm). This is a low luminosity ($L = 7.5 L_\odot$; Tobin et al. 2007) protostellar source located in the Perseus Molecular Cloud (D $\sim$ 250 pc; e.g., Enoch et al. 2006). A powerful and highly collimated flow is driven by this source, as testified by interferometric CO and SiO maps (Guilloteau et al. 1992; Bachiller et al. 1995). This highly collimated molecular jet is associated with a less collimated and energetic CO outflow, probably representing ambient swept-up material. Near-IR observations performed on the L1448-C outflow show that H$_2$ hot molecular gas is detected only at the bow shocks at a distance of $\sim 1''$ from the central source; the underlying jet that is responsible for the shocks remains undetected at optical and near-IR wavelengths and has been traced at millimeter wavelengths as collimated SiO emission (Guilloteau et al. 1992). Far-IR observations performed with ISO have shown the existence of a warm gas component ($T \sim 1000$ K, $n \sim 10^3$ cm$^{-3}$) associated with the molecular jet, showing up in [O i] 63 $\mu$m, H$_2$, CO, and H$_2$O pure rotational emission (Nisini et al. 1999, 2000; Froebrich et al. 2002). Recent Spitzer-IRAC and MIPS images have shown that the source is actually binary, with a separation of $\sim 7''$ (Jørgensen et al. 2006; Tobin et al. 2007). The north/south binary components are called L1448-CN and CS (Jørgensen et al. 2006) or L1448-mm A and B (Tobin et al. 2007), respectively. We will use the Jørgensen et al. (2006) nomenclature in this paper. Of the two sources, the CN component is associated with the strong millimeter source recognized by interferometric observations as the outflow driving source (Bachiller et al. 1995).

The paper is organized as follows: Section 2 describes the Spitzer observations and data reduction as well as additional near-IR observations obtained at the UKIRT telescope. Sections 3 and 4 contain our analysis of the observed H$_2$ and fine structure lines in order to derive the main physical parameters of the jet. Finally, conclusions are presented in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. SPITZER-IRS

The driving source and outflow of the Class 0 object L1448-C were observed with the Spitzer Infrared Spectrograph (Houck et al. 2004) during 2006 March and September. Four positions have been targeted with the short–high (SH) and long–high (LH) IRS modules ($R \sim 600$, 10–37 $\mu$m) in order to cover the central driving source (L1448-CN), the southern CS source (the position of which spatially coincides with a CO redshifted clump of extremely high velocity (EHV) jet emission named R1; Bachiller et al. 1990), and two adjacent positions along the blue shifted part of the jet, that we call OF1 and OF2, the first comprising the B1 mm clump in Bachiller et al. (1990) and the second the H$_2$ bow shock, as detected in the near-IR image of the flow by Davis & Smith (1996), respectively (see Figure 1). The plate scale of the detector is 2.3 pixel$^{-1}$ and 4.5 pixel$^{-1}$ for the SH and LH modules, respectively. Observations with the short–low (SL) module ($R \sim 60$–120, pixel scale 1.8 pixel$^{-1}$) were also acquired to extend the spectral coverage down to 5 $\mu$m. The observing period was chosen in order to have the SL slit aligned along the L1448 jet. The observations were performed in staring mode with a total integration time of 2.5 hr per position.

The data were reduced and calibrated with the S13 pipeline. Basic calibrated data (bcd images) were median-combined and cleaned for rogue pixels with the IRS CLEAN MASK routine, and additional bad pixels in the low resolution module were removed by visual inspection. Spectral extraction was performed with the Spitzer IRS Custom Extraction tool (SPICE). For the high-resolution modules the full slit was extracted, whereas for the SL module, the full slit length was divided into four equal regions ($\sim 14''$) that were consecutively extracted in order to best match the high-resolution module pointings. High-resolution spectra were defringed using the IRSFRINGE package while the zodiacal light contribution was estimated using the Spitzer Planning Observations Tool (SPOT) and subtracted. Inter-order flux offset and curvature effects were minimized by optimally selecting the best approximation between the point and extended source calibration options (SPICE), according to the morphology of each observed region. The resulting line flux difference between the two extraction methods is $\sim 20\%$, which can be considered as an upper limit to the error for the observed line fluxes.

The calibrated spectra combined for all modules at each position are presented in Figure 2; in the same figure open squares and triangles represent IRAC bands 3, 4, and MIPS band 1 continuum flux measurements from the recent studies of the region by Jørgensen et al. (2006) and Tobin et al. (2007), respectively. Their good agreement with the extracted spectra baseline confirms the appropriateness of the adopted extraction and calibration techniques. In particular, the procedure for zodiacal light subtraction is sufficiently precise to cancel the baseline jumps between different modules, the only exception being the SH and LH modules at the CS position, around 20 $\mu$m.

The extracted spectra display a number of emission lines that arise both from molecular and forbidden atomic or ionic transitions. Line identification has been performed considering the features lying more than $3\sigma$ above the local rms and whose emission peak, fitted by a gaussian, is within half a resolution element from the theoretical vacuum wavelength. The observed molecular emission lines are due to H$_2$, where the full series of pure rotational transitions (S(0)–S(7)) in the given wavelength range of the instrument are detected. Atomic and ionic emission

![Figure 1](image-url)
has been detected in the form of the fundamental fine-structure lines from [Fe ii] at 25.98 μm, [S i] at 25.25 μm, and [Si ii] at 34.81 μm (see Figure 3). None of the other numerous higher excitation [Fe ii] lines falling in the investigated wavelength range has been detected at the 3σ level: this fact, combined with the nondetection of the [Ne ii] line at 12.8 μm, already suggests that the investigated region presents very low excitation conditions.

In addition to emission lines, wide absorption bands are also observed in the spectra extracted at the two sources, the most prominent being those due to silicates at 9.7 μm, water ice at 6.02 μm, and CO2 ice at 15.2 μm.

Fluxes of the individual lines were computed by the Gaussian fitting after subtracting a sloped baseline within the Spectroscopic Modeling, Analysis and Reduction Tool (SMART; Higdon et al. 2004). In Table 1, we report the parameters of the detected lines, along with their identified transitions and the associated rms errors given by the 1σ uncertainty derived from the fluctuations of the local baseline. The measured fluxes have a larger uncertainty of up to 20% given by the flux calibration uncertainty. The 0–0 S(2) line has been observed by both the SL and SH modules. The line fluxes measured in the two modules agree inside the errors with the ex-
Figure 3. Magnification of the spectra presented in Figure 2 displaying the ionic lines.

| λ (μm) | Element (Transition) | Module | F ± ΔF (10^{-14} erg cm^{-2} s^{-1}) |
|--------|----------------------|--------|-----------------------------------|
|        |                      |        | CS  | CN  | OF1 | OF2 |
| 5.51116 | H2 0–0 S(7)         | SL     | 5.5 ± 1.5 | 4.5 ± 0.1 | 3.8 ± 0.6 | 3.9 ± 0.2 |
| 6.10856 | H2 0–0 S(6)         | SL     | < 0.7   | 2.1 ± 0.5 | 1.7 ± 0.3 | 4.8 ± 0.9 |
| 6.90952 | H2 0–0 S(5)         | SL     | 3.2 ± 1.0 | 7.8 ± 0.6 | 6.4 ± 0.6 | 9.3 ± 0.5 |
| 8.02505 | H2 0–0 S(4)         | SL     | < 2     | 7.0 ± 1.5 | 2.8 ± 0.7 | 4.5 ± 0.2 |
| 9.66491 | H2 0–0 S(3)         | SL     | < 0.5   | 4.9 ± 0.7 | 10.8 ± 2.2 | 20.1 ± 0.3 |
| 12.2786 | H2 0–0 S(2)         | SL     | 1.1 ± 0.4 | 2.8 ± 0.7 | 3.5 ± 0.4 | 4.0 ± 0.4 |
| 12.2786 | H2 0–0 S(2)         | SH     | 1.7 ± 0.2 | 2.9 ± 0.2 | 3.3 ± 0.2 | 8.4 ± 0.3 |
| 17.0348 | H2 0–0 S(1)         | SH     | 0.4 ± 0.1 | 2.4 ± 0.1 | 3.2 ± 0.2 | 5.7 ± 0.1 |
| 28.2188 | H2 0–0 S(0)         | LH     | < 0.6   | < 1   | 1.2 ± 0.4 | 2.1 ± 0.3 |
| 5.33042 | H2 1–1 S(8)         | SL     | < 0.8   | < 2   | < 1.3 | < 2 |
| 5.81112 | H2 1–1 S(7)         | SL     | < 0.8   | < 1   | < 1   | < 1.6 |
| 6.43710 | H2 1–1 S(6)         | SL     | < 1.3   | < 1.7 | < 1.2 | < 1.8 |
| 7.28070 | H2 1–1 S(5)         | SL     | < 2     | < 1.6 | < 1.5 | < 0.9 |
| 8.45367 | H2 1–1 S(4)         | SL     | < 1.2   | < 0.8 | < 0.5 | < 0.8 |
| 10.1777 | H2 1–1 S(3)         | SL     | < 0.5   | < 0.8 | < 0.9 | < 0.8 |
| 12.9275 | H2 1–1 S(2)         | SL     | < 0.8   | < 0.5 | < 0.8 | < 1.8 |
| 17.9320 | H2 1–1 S(1)         | SH     | < 0.5   | < 0.6 | < 0.4 | < 0.4 |
| 25.7017 | H2 1–1 S(0)         | LH     | < 2     | < 2   | < 0.9 | < 0.8 |
| 5.34017 | [Fe ii] ^4F_9/2–^4F_7/2 | SL     | < 2     | < 1   | < 2   | < 3 |
| 17.9359 | [Fe ii] ^4F_9/2–^4F_7/2 | SH     | < 0.4   | < 0.3 | < 0.5 | < 0.4 |
| 25.9883 | [Fe ii] ^4D_5/2–^4D_3/2 | LH     | < 1     | 9.7 ± 0.4 | 1.2 ± 0.1 | 4.2 ± 0.1 |
| 35.7774 | [Fe ii] ^4F_9/2–^4F_7/2 | LH     | < 2     | < 3   | < 3   | < 1.5 |
| 25.2490 | [S i] ^3P_0–^3P_2 | LH     | 5.8 ± 0.3 | 15.2 ± 0.5 | 3.2 ± 0.2 | 6.8 ± 0.2 |
| 25.2490 | [S i] ^3P_1–^3P_2 | LH     | 5.3 ± 0.4 | 19.2 ± 0.5 | 2.6 ± 1.2 | 6.1 ± 0.2 |
| 34.8152 | [Si i] ^3P_3/2–^3P_1/2 | LH     | < 8     | 12.9 ± 4.2 | < 3 | 5.6 ± 0.6 |

Note. a The [S i] 25.2 μm line is detected in two different orders of the LH module.

In the same table, we also give the upper limits for a set of nondetected lines that fall within the observed range and that will be used in the analysis that follows. In a previous study of the same region with ISO/SWS, Nisini et al. (1999) detected the S(3) to S(5) H2 transitions in a region of 14′′ × 27′′ cen-
tered on the L1448-C source. The derived fluxes are a factor between 3 and 8 larger than the ones presented here. The field of view (FOV) of the SWS observations is around 10 times larger than the region extracted in our spectra; therefore, the observed flux difference can be attributed to the different adopted apertures.

2.2. UKIRT–UIST

In order to further investigate the excitation conditions along the jet axis, additional spectra, covering the wavelength range from 1.4 to 2.5 μm, were obtained on 2006 October 4th at UKIRT (UK Infrared Telescope) using the image spectrometer UIST in spectroscopic mode. A 4 pixel wide slit was used with a pixel scale of 0″.12, corresponding to a spectral resolution ~500–700. The slit was positioned roughly parallel with the jet axis, and thus, aligned with the SL IRS slit, at a position angle (P.A.) of −17°. Object-sky–sky-object sequences were made with a total exposure time of 300 s for each one. Each spectral image was bias subtracted and flat fielded using the ORAC data-reduction software. Further reduction was performed using the IRAF standard tasks. An Argon lamp was used in order to wavelength calibrate the spectra. B-type stars were observed with the same configuration in order to remove the telluric features and flux calibrate the spectra. Once the reduction was completed, the APALL IRAF task was used to extract the spectra corresponding in length to the four regions investigated with IRS. Table 2 lists the lines detected in the CN, OF1, and OF2 regions, with the corresponding measured flux. No lines have been detected in the CS position. Only H2 1–0 and 2–1 rovibrational lines were detected, while any atomic or ionic emission (e.g., the strong [Fe II] lines at 1.25 μm and 1.64 μm) is missing, as already evidenced by Caratti o Garatti et al. (2006).

It can be noted that in the OF2 position, which corresponds to the bow shock position, a large number of transitions from higher excitation 1–0 lines (up to S(9)) are detected. This may be indicative of higher excitation conditions associated with the bow shock or lower reddening pertaining to this region since it is located far from the millimeter source core.

Table 2 L1448 Observed Lines:UKIRT/UIST

| λ (μm) | Element (Transition) | F ± ΔF (10⁻¹⁶ erg cm⁻² s⁻¹) |
|--------|----------------------|-------------------------------|
| 1.6877 | H2 1–0 S (9)         | <0.3                         |
| 1.7147 | H2 1–0 S (8)         | <0.4                         |
| 1.7880 | H2 1–0 S (6)         | <0.4                         |
| 1.9576 | H2 1–0 S (3)         | <0.4                         |
| 2.0338 | H2 1–0 S (2)         | 1.36 ± 0.05                  |
| 2.0735 | H2 2–1 S (3)         | <0.5                         |
| 2.1218 | H2 1–0 S (1)         | 3.51 ± 0.33                  |
| 2.1542 | H2 2–1 S (2)         | <0.4                         |
| 2.2235 | H2 1–0 S (0)         | <0.4                         |
| 2.2477 | H2 2–1 S (1)         | <0.4                         |
| 2.3556 | H2 2–1 S (0)         | <0.3                         |
| 2.4066 | H2 1–0 Q (1)         | 8.07 ± 0.39                  |
| 2.4134 | H2 1–0 Q (2)         | 3.28 ± 0.36                  |
| 2.4237 | H2 1–0 Q (3)         | 8.01 ± 0.37                  |
| 2.4375 | H2 1–0 Q (4)         | 1.49 ± 0.28                  |
| 2.4548 | H2 1–0 Q (5)         | 5.89 ± 0.30                  |
| 2.4756 | H2 1–0 Q (6)         | <0.4                         |
| 2.5001 | H2 1–0 Q (7)         | <0.5                         |

Figure 4. Ratio of the atomic ([Fe II] 26 μm and [S i] 25 μm) over the molecular (H2 S(1)) line emission. The atomic emission dominates close to the driving source (CN) while the atomic/molecular contribution decreases in the OF1 and OF2 positions (see Figure 1).

3. ANALYSIS OF THE EXCITATION CONDITIONS ALONG THE JET

3.1. Extinction and Spatial Variation of Line Luminosity

Optical extinction (A_V) values along the line of sight of the CS and CN sources have been measured from the 9.7 μm silicate absorption feature, adopting the relationship between the optical depth of this feature and the visual extinction given by Mathis (1998), i.e., A_V/τ_9.7 = 19.3 mag. The derived A_V values are 32 and 11 mag for the CS and CN sources, respectively. In the OF1 and OF2 positions, no silicate absorption is detected so no direct measurement of A_V from our spectra is possible. We have therefore assumed an extinction of 5 mag, as derived by Nisini et al. (2000) toward the direction of the B1 clump (coincident with the OF1 position). Such a low value of extinction is in agreement with the absence of water and CO 2 ice absorption features in the spectra of these positions, as these features should become detectable in the Spitzer spectra only once the visual extinction reaches values above 4.5 ± 1.0 mag (Whittet et al. 2007). All the individual detected lines have been dereddened adopting these A_V values and the different extinction laws appropriate for the considered wavelength ranges: in the range from 1 to 13 μm the extinction law of Rieke & Lebofsky (1985) was adopted while from 13 to 23 μm the extinction law of Mathis (1998) was used, which was extrapolated to 28 μm.

An a posteriori check of the correctness of the adopted extinction values was done using the Boltzmann diagrams constructed from the H2 near- and mid-IR lines (see Section 3.2), by examining the fit to a straight line of transitions appropriate for the 9.7 μm silicate absorption (like the 0–0 S(3) line at 9.67 μm) and at the interface between the near- and mid-IR lines in the same plot.

Once extinction corrected, we have explored the spatial variation of the relative atomic/molecular emission, by plotting the ratio of the [Fe II] 26 μm and [S i] 25 μm with respect to the H2 0–0 S(1) line (Figure 4). This plot clearly shows that the relative brightness of the atomic component with respect to the molecular component sharply decreases going from the CN to the OF1 position while only slightly increasing again at the bow shock.
position. A similar behavior has been observed in the near-IR for a number of Class I jets, where the atomic and molecular components have been traced by the [Fe II] 1.64 μm and H2 1–0 S(1) lines respectively (Nisini et al. 2002, 2005). In these sources, the relative decrease of atomic gas emission with respect to H2 in the jet beams is accompanied by a decrease of excitation in the jet which occurs on scales of ~5′–10′ from the driving source. The interpretation of this behavior is that the jet, heated and ionized in the acceleration region, progressively expands and cools down until it strongly interacts with the medium through a bow shock. The spatial scale of the IRS instrument is too poor to resolve the intensity and excitation variations within the jet expansion region; a qualitative inspection, however, suggests a similar behavior, in spite of the different physical conditions pertaining to the L1448 jet.

3.2. H2 Emission

Being very easily thermalized, H2 lines can be used as probes for the temperature by means of excitation diagrams. The latter are constructed by plotting the values of ln(Nv,J/g) against £vn,J, where Nv,J is the column density for the population at the upper level, £v,J and g are the level energy and statistical weight respectively. Assuming LTE conditions, these two quantities are linearly related, and the local temperature can be derived from the slope of the fit. We have constructed excitation diagrams in each position combining the Spitzer and UKIRT observed lines. For these, column densities have been derived dividing the line flux for the aperture adopted for the spectral extraction, assuming that the emission is extended and fills the extraction lines. For these, column densities have been derived dividing the line flux for the aperture adopted for the spectral extraction, assuming that the emission is extended and fills the extraction apertures in a uniform way. This cannot be the case for the 0–0 S(0) line observed with the much larger aperture of the LH module; the H2 fundamental transition should in fact also be affected by diffuse emission from the cloud; therefore the derived column density can be considered as an upper limit of the S(0) column density in the jet. In constructing the Boltzmann diagrams, we have assumed an H2 ortho/para ratio equal to the equilibrium value of 3. We do not appreciate significant variations from this value inside the errors of the data points.

The excitation diagrams for each position are presented in Figure 5; in these, Spitzer (open circles) and UKIRT lines (open squares) are least square fitted with a straight line. The visual extinction values used and temperatures derived from the slope of the fitted lines are displayed in the upper left corner of each panel. The derived temperatures and column densities for each of the observed regions are presented in Table 3. The gas temperature shows a slight decrease going from the driving source (CN) to the OF1 position, while column density displays a constant increase from the CS to the OF2 positions. This trend confirms that the excitation conditions decrease as the jet propagates into the ambient medium, and that in the inner region the jet is mostly atomic, as testified from the [Fe II]/H2 ratio displayed in Figure 4.

3.2.1. Shock Model

As seen in the previous section, the H2 Boltzmann diagram in the OF2 position shows the presence of different temperature components, likely arising in the unresolved cooling zone behind the bow shock. In order to constrain the shock conditions from our Spitzer and UKIRT observations, we have attempted to model the derived H2 column densities with a C-type bow shock model (Smith 1991). For a better comparison of the derived column density with the model fit, we have constructed a column density ratio (CDR) plot, in which the column density in the upper energy level of each transition has been normalized of the excitation diagram, which is equal to ln(N(H2)/Q(T), with Q(T) is the partition function at temperature T. The derived temperatures and column densities for each of the observed regions are presented in Table 3. The gas temperature shows a slight decrease going from the driving source (CN) to the OF1 position, while column density displays a constant increase from the CS to the OF2 positions. This trend confirms that the excitation conditions decrease as the jet propagates into the ambient medium, and that in the inner region the jet is mostly atomic, as testified from the [Fe II]/H2 ratio displayed in Figure 4.

![Figure 5. Excitation diagram of the H2 lines for each position defined in Figure 1. Spitzer (open circles) and UKIRT (open squares and arrows for the upper limits) data points are optimally least square fitted (solid line). Temperatures and total column densities are derived from the slope of the fitted line, and its intersection with the ln(Nv,J/g) axis. Visual extinction values used for dereddening and derived temperatures are displayed in the upper left corner of each panel.](image)
to the value given by a gas at 1000 K. These values are then presented relative to the column of the 1–0 S(1) upper energy of 6953 K (see Figure 6). In this figure, triangles represent Spitzer 0–0 lines, squares represent all lines originating from the first vibrational levels, including the 1–1 upper limits derived from the Spitzer IRS spectra, and diamonds correspond to 2–1 S lines. The superimposed model predictions are for the ground (solid), first (dashed) and second (dot-dashed line) vibrational level. The fit corresponds to a bow shock moving at 100 km s$^{-1}$ into a medium of total density $10^{3}$ cm$^{-3}$.

Figure 6. CDR diagram of the OF2 position, constructed normalizing the column density of each transition to the value given by a gas at 1000 K and to the 1–0 S(1) column density. Triangles represent Spitzer 0–0 lines, squares represent lines from the first vibrational levels, including the 1–1 upper limits derived from the Spitzer IRS spectra, and diamonds correspond to 2–1 S lines. The superimposed model predictions are for the ground (solid), first (dashed) and second (dot-dashed line) vibrational level. The fit corresponds to a bow shock moving at 100 km s$^{-1}$ into a medium of total density $10^{3}$ cm$^{-3}$.

3.3. Atomic Jet

As pointed out in Section 2.1, the detection of only the fundamental [Fe ii] transition indicates that the excitation conditions of the atomic jet are very low. The [Fe ii] 26 $\mu$m line originates from the $^{6}D_{7/2}$ level, which has an excitation temperature of $\sim$ 550 K, while the level just above this one, $^{6}D_{5/2}$, gives origin to a transition at 35 $\mu$m having $T_{\text{ex}} \sim$ 960 K. In principle, the nondetection of the 35 $\mu$m transition could give a strong constraint on the gas temperature. However, the spectral region around 30 $\mu$m is very noisy and the upper limits are not stringent. To get constraints on the temperature, we have instead considered the upper limit on the $^{4}F_{7/2} - ^{4}F_{9/2}$ transition at 18 $\mu$m, that lies in a region of lower noise. In addition, we have also used the ratio [Si i] 35 $\mu$m/[Fe ii] 26 $\mu$m as a density probe. Si and Fe have a comparable ionization potential (8.15 and 7.9 eV respectively) and thus a similar degree of ionization. Furthermore, these two lines are excited at a similar temperature of $\sim$ 500 K; thus their ratio depends only on the electron density and the [Si/Fe] gas-phase abundance ratio. We assume an [Si/Fe]$_{\text{gas}}$ ratio equal to the solar ratio (taken from Girart & Acord 2001), an assumption implying that the two species are equally depleted on grains. The validity of this assumption is further examined in Section 4.

Figure 7 presents a plot of the [Si i] 34.8 $\mu$m/[Fe ii] 26.0 $\mu$m ratio as a function of the electron density, for temperatures of 1000 K and 2000 K (solid and dashed lines). This diagram has been constructed employing a statistical equilibrium model that considers the first 16 levels for [Fe ii] (Nisini et al. 2002), and a two-level system for [Si i]. Radiative and collisional rates for the [Si i] have been taken from Dufon & Kingston (1991). Hatched areas represent the ratios observed in the CN and OF2 regions, respectively. Such observations are consistent with values of $n_{e}$ in the range $\sim$ 300–500 for the OF2 position and $\sim$ 200–1000 cm$^{-3}$ for the CN position.

In Figure 8, the upper limit ratio [Fe ii] 18 $\mu$m to 26 $\mu$m is plotted as a function of the gas temperature, for different electron density values. The 26 $\mu$m line flux and the 18 $\mu$m line upper limit have been measured on two IRS modules having different FOV, and therefore, their intrinsic ratio depends upon the extension of the emitting region. A conservative upper limit on this ratio is obtained assuming beam filling and consequently normalizing the line ratio to the different FOV. The upper limits obtained in this manner are displayed in Figure 8 for the CN and OF2 regions. From this plot, we derive that gas temperatures less than $\sim$ 2500 K and $\sim$ 1500 K are responsible for the emission observed in the OF2 and CN positions, respectively.

Figure 7. Diagnostic diagram of the [Si i] 35 $\mu$m/[Fe ii] 26 $\mu$m ratio vs. electron density, for temperatures of 1000 K and 2000 K (solid and dashed lines). Hatched areas represent the observed ratio for the CN and OF2 regions that correspond to electron densities of from 200 to 1000 cm$^{-3}$ and from 300 to 5000 cm$^{-3}$, respectively.

(A color version of this figure is available in the online journal.)
The derived physical conditions significantly differ from the conditions measured from [Fe II] near-IR lines in jets from more evolved class I sources, that have temperatures ranging from 7000 and 15000 K and densities \( \sim 10^{2}–10^{5} \text{ cm}^{-3} \) (e.g., Nisini et al. 2002; Takami et al. 2004). The low electron density values, in particular, point to a low ionization fraction for the gas under consideration. Total \( n_{\text{H}} \) densities of the order of \( 10^{5} \text{ cm}^{-3} \) or higher have been inferred in the L1448 jet from submillimeter and far-IR observations (Nisini et al. 2000, 2007), implying an ionization fraction \( x_{e} \) of \( \sim 10^{-2} \) or lower.

The inferred low temperature and ionization fraction, in conjunction with the nondetection of the [Ne ii] 12.8 \( \mu \text{m} \) line, imply that, if these lines are shock excited, the shock velocity should be low. Fast J-type shocks (e.g., Hollenbach & Mc Kee 1989) are therefore excluded. Low-velocity J-type shocks might provide sufficient ionization to excite the fundamental ionic fine-structure lines, but the shock velocity needs to be lower than \( \sim 10 \text{ km s}^{-1} \) to have a temperature of less than \( \sim 2000 \text{ K} \).

Part or all of the atomic emission observed on-source may in principle also originate from excitation in a circumstellar disk. Line emission disk models (Gorti & Hollenbach 2008) as well as Spitzer observations in T Tauri disks (e.g., Pascucci et al. 2007; Lahuis et al. 2007) show, however, that disk emission is characterized by both strong [Ne ii] 12.8 \( \mu \text{m} \), excited in the high temperature gas heated and ionized at the disk surface, and [Fe ii] 24 \( \mu \text{m} \) line, originating in the deeper disk vertical layers, that we do not detect here.

The strong atomic emission observed on-source may instead originate from the jet base, in a zone similar to the forbidden emission line (FEL) regions observed in Class I/II jets although with very different excitation conditions (e.g., Davis et al. 2003). In analogy with the FEL regions there is a decrease in intensity of the atomic emission with distance from the source, likely caused by the expansion of the jet and the consequent cooling down of the gas.

4. DUST DISRUPTION AND ABUNDANCE OF REFRACTORY SPECIES

Gas-phase abundances of iron and silicon are very low in the interstellar medium since these refractory elements are easily depleted onto the cores of dust grains. Shocks occurring along the outflows of young stars are able to at least partially restore the refractory elements to the gas phase, through processes like sputtering and grain–grain collisions (Jones 2000). Observations of millimeter and submillimeter SiO lines in many molecular outflows (e.g., Codella et al. 2007; Gibb et al. 2007; Nisini et al. 2007) have shown that dust grains are indeed partially destroyed, and that the released Si undergoes chemical reactions leading to the formation of SiO (Schilke et al. 1997; Gudserf et al. 2008). SiO abundance determinations along the molecular jet of L1448 show however that gas-phase Si locked in SiO is only about 5 \( \times 10^{-3} \) of the Si solar abundance: thus either not all of the Si released by the dust reprocessing is converted into SiO, or the shocks are not able to completely restore all the Si to the gas phase. The detection of the [Si ii] fundamental line in our spectra suggests that indeed a significant part of gas-phase Si is present in an ionic form. On the other hand, the gas-phase abundance of Fe in jets has been so far measured only in near-IR jets of Class I sources, from the bright near-IR [Fe ii] lines (Nisini et al. 2002, 2005; Podio et al. 2006). Such studies have shown that a large fraction of Fe (from 70% to 95%) is still locked in grains, indicating that dust grains have not been totally destroyed by shocks. No estimates have so far been given about the iron gas-phase abundance in Class 0 molecular outflows. We can now provide abundance estimates of both Si and Fe through the detected emission lines of their single-ionized atoms.

The gas-phase abundance of refractory elements can be derived from a comparison of their emission lines with those of a nonrefractory species emitted under the same physical conditions. In the case of our spectra, the [S i] 25.2 \( \mu \text{m} \) line can be used as a reference, as sulphur is not depleted in grains, assuming that all the sulphur is in neutral form. To check this hypothesis, we have computed the S\(^+\)/S\(^-\) ratio applying ionization equilibrium between collisional and charge-exchange ionization, and direct/dielectric recombination (rates from Stancil et al. 1998; Landini & Monsignori Fossi 1990). For the inferred physical conditions of \( T \sim 1000–2000 \text{ K} \) and \( x_{e} \lesssim 10^{-2} \), it results that 95% of S is in neutral form. The iron gas-phase abundance, relative to the solar value, can therefore be written as

\[
\frac{[\text{Fe}]_{\text{gas}}}{[\text{Fe}]_{\odot}} = \frac{[\text{Fe}/S]}{[\text{Fe}/S]_{\odot}} \times \frac{F([\text{Fe} \, \text{II}] 25.2 \mu \text{m})}{F([\text{Si} \, \text{I}] 25.2 \mu \text{m})} \times [\text{S}/\text{Fe}]_{\odot}
\]

where \( [\text{S}/\text{Fe}]_{\odot} = 7 \times 10^{-4} \) is the solar abundance ratio, taken from Asplund et al. (2005), and \( F([\text{Fe} \, \text{I}] 26 \mu \text{m})/F([\text{Si} \, \text{I}] 25.2 \mu \text{m}) \) is the observed ratio. A similar expression can be written for the [S i] 25.2 \( \mu \text{m} \) line, with \( [\text{S}/\text{Fe}]_{\odot} \) the solar abundance ratio.

Two values of temperatures have been considered: 2500 K (the upper limit derived in the OF2 position) and 600 K (the lower value derived by the H\(_2\) analysis). In a medium with high total density and low ionization fraction, such as the one we are considering here, collisions with atomic hydrogen may become important in the excitation of atomic species such as [S i], in...
spite of the low $n_H$ collisional de-excitation rates with respect to the rates for electronic collisions ($\gamma_e/\gamma_n \sim 10^{-4}$ for the [S i] 25 $\mu$m line; Hollenbach & McKee 1989). In order to assess how collisions with hydrogen affect the results, we have calculated the emissivities also assuming a medium with a total density of $10^3$ cm$^{-3}$ and $n_H = 0.1$ n$_{\text{tot}}$.6

We have applied the above analysis to the values observed in the CN, OF1, and OF2 positions: for the [S i] 25 $\mu$m flux, we have taken the average value given by the determinations obtained in the two different orders of the LH module. Results are summarized in Table 4: the uncertainty in temperature results in a factor of twice the uncertainty in derived abundances, while a difference of 4 is found between results obtained assuming collisions with electrons and with atomic hydrogen.

The table shows that the gas-phase abundance of Fe and Si remains between 5% and 20% of the solar values for both species and in all positions. Similar low values of Fe abundances have also been found in the inner regions of jets from Class I sources from the analysis of the [Fe ii] NIR lines (Nisini et al. 2005; Podio et al. 2006), while larger abundances (from 20% to 70% of the solar value) have been derived at large distances from the driving source and in bow shocks (Nisini et al. 2002; Giannini et al. 2008).

Finally, taking an SiO abundance of $5 \times 10^{-3}$ derived by Gusdorf et al. (2008), the Si/SiO abundance ratio is $\sim 100$, giving support to the hypothesis that most of the silicon released from grains remains in atomic form.

5. MASS AND MASS FLUX IN THE WARM GAS

The presented observations point to the presence of warm gas associated with the L1448 CO and SiO millimeter jet, composed of both a molecular and a weakly ionized component. We can assess if this warm gas represents a dynamically important component of the jet, by measuring its mass flux and comparing it with estimates of the mass flux based on ISO and submillimeter observations of the CO emission (Nisini et al. 2000; Bachiller et al. 1990). We can determine the mass flux for both the molecular and atomic counterparts of the outflow, using as tracers H$_2$ and [Fe ii]/[S i] respectively. The method is similar in both cases and is based on the fact that the line emission is optically thin, so that the observed luminosity is proportional to the mass of the emitting gas (Hartigan et al. 1994). For [Fe ii] and [S i] we have applied the relationship given in Nisini et al. (2005):

$$M = \mu m_{\text{H}} \times \left( n_{\text{H}} V \right) \times (dV/dl_i) \tag{2}$$

where $\mu$ is the mean atomic weight, $m_{\text{H}}$ is the proton mass, $n_{\text{H}}$ is the total number density, $V$ is the volume of the emitting region, $dl_i$ is the projected length perpendicular to the line of sight, and $dV$ is the tangential velocity of the observed region.

The number of emitting atoms can be derived from the line luminosity according to the relation

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

where $A_i$ and $f_i$ are the radiative rate and fractional population of the upper level, and $[X/H]$ is the gas-phase abundance of the considered atom/ion. For the determination of the mass flux from the [Fe ii] 26 $\mu$m line, we have assumed that all iron is singly ionized based on the fact that neutral iron lines are observed within the IRS range; this assumption is based on the fact that the [Fe i] ground transition at 24 $\mu$m is not detected in any of our spectra, in spite of its high radiative rate coefficient, comparable to that of the [Fe ii] ground transition. We have taken the iron gas-phase abundance estimated in Section 3.1 and listed in Table 4. Conversely, to apply Equation (3) to the [S i] 25 $\mu$m line, we have assumed that sulphur is all neutral (as discussed in Section 3.1) and taken the sulphur solar abundance.

The projected length $dl_i$ was taken equal to the jet length sampled by the width of the LH slit. Finally, the tangential velocity of the outflow was taken equal to 170 km s$^{-1}$ as derived from the SiO proper motion study by Girart & Acord (2001). Such a velocity, appropriate for the submillimeter jet, may be just a lower limit for the atomic jet velocity, if the latter is associated with a higher velocity inner component. It has been shown however that atomic jets from Class I/II sources have velocities in the range of 100–300 km s$^{-1}$ (Ray et al. 2007; Davis et al. 2003). We, therefore, believe that our assumption can introduce an uncertainty of at most a factor of 2 in the mass-flux determination. The derived mass-flux values using the above method are listed in Table 5. The uncertainty associated with the Fe gas-phase abundance results in an order of magnitude uncertainty in the mass flux determination using the [Fe ii] 26 $\mu$m. The determinations from the [S i] line agree with the range of values derived from [Fe ii] and indicate a mass flux of the order of $(1–2) \times 10^{-6} M_\odot$ yr$^{-1}$ in the CN position, while lower values, of the order of $(3–8) \times 10^{-7} M_\odot$ yr$^{-1}$, are estimated at the bow shock OF2 position.

The determination of the mass flux from the H$_2$ component has been measured instead from the total column density for each extracted region as derived from the excitation diagrams, applying the relationship

$$M = \mu m_{\text{H}} \times \left( 2N(H_2)A \right) \times (dV/dl_i), \tag{4}$$

where $N(H_2)$ is the total column density and $A$ is the area sampled by the slit. We consider here again the tangential velocity as measured from the SiO proper motion, assuming that it is representative of all the molecular gas. The derived mass flux along the outflow with this method is presented in Table 5. The H$_2$ mass flux in the central position is about 2 orders of

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**Table 4**

| Position  | CN   | OF1   | OF2   |
|-----------|------|-------|-------|
| $[\text{Fe}^{\text{ii}}]/[\text{Fe}^{\text{ii}}]$ | $3–5 \times 10^{-2}$ | $4–7 \times 10^{-2}$ | $3–5 \times 10^{-2}$ |
| $[\text{Fe}^{\text{ii}}]/[\text{Fe}^{\text{ii}}]$ | $1–2 \times 10^{-1}$ | $1.5–3 \times 10^{-1}$ | $1–2 \times 10^{-1}$ |
| $[\text{Si}^{\text{ii}}]/[\text{Si}^{\text{ii}}]$ | $3–5 \times 10^{-2}$ | ... | $3–5 \times 10^{-2}$ |
| $[\text{Si}^{\text{ii}}]/[\text{Si}^{\text{ii}}]$ | $1–2 \times 10^{-1}$ | ... | $1–2 \times 10^{-1}$ |

Notes:

- Assuming collisions with electrons and $n_e = 400$ cm$^{-3}$.
- Assuming collisions with $n_H$, $n_{\text{tot}} = 10^3$ cm$^{-3}$, and $n_H = 0.1$ n$_{\text{tot}}$.

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**Table 5**

| Position  | $M(\text{H}_2)$ | $M([\text{Si}^{\text{ii}}])$ | $M([\text{Fe}^{\text{ii}}])$ |
|-----------|-----------------|----------------|----------------|
| CN        | 0.5             | 9–20           | 2–20           |
| OF2       | 1.4             | 3–8            | 0.9–9          |

where $\mu$ is the mean atomic weight, $m_{\text{H}}$ is the proton mass, $n_{\text{H}}$ is the total number density, $V$ is the volume of the emitting region, $dl_i$ is the projected length perpendicular to the line of sight, and $dV$ is the tangential velocity of the observed region.
magnitude lower than the value derived from the atomic lines while in the OF2 position $M$(H$_2$) is a factor between 2 and 5 lower than $M$([S I]). Thus, the bulk of the flowing mass is carried out by the atomic jet all along the sampled positions.

A mass flux of the order of $5 \times 10^{-6} M_\odot$ yr$^{-1}$ has been derived within 20$'$ of the driving source combining multitransition CO submillimeter and ISO data (Nisini et al. 2000). This value is only a few factors larger than the value we derive from atomic lines at the CN position, which suggests that the atomic jet detected by our observations and the warm CO outflows sampled by the ISO and submillimeter observations are dynamically linked. It is also instructive to examine if the atomic jet detected by our Spitzer observations possesses enough momentum to sustain the entrained CO outflow observed at millimeter wavelength. Bachiller et al. (1990) derived, for the L1448-mm blueshifted lobe, a momentum flux of the order of $2.6 \times 10^{-4} M_\odot$ km s$^{-1}$ yr$^{-1}$, assuming an outflow inclination of 70$'$ with respect to the plane of the sky. If we assume momentum conservation for entrainment of the outflow by the jet, and a total jet velocity of 170 km s$^{-1}$, we derive that the primary jet should possess a mass flux of the order of $1.4 \times 10^{-5} M_\odot$ yr$^{-1}$. This is consistent with the values we infer from the atomic emission, supporting the hypothesis that the detected atomic jet represents the energetically most important component of the outflow.

The accretion rate can also be estimated assuming the bolometric luminosity is mainly due to accretion. Using a stellar mass $M_* \sim 0.5 M_\odot$ (Froebrich et al. 2003) and a stellar radius $R_* \sim 4 R_\odot$ (Stahler et al. 1980), we get an accretion rate $\dot{M}_{\text{acc}} \sim L_{\text{bol}} R_*/GM_* \sim 2 \times 10^{-6} M_\odot$ yr$^{-1}$. We thus derive a value comparable to the mass ejection rate estimated above. This is inconsistent with the picture that the accretion only at the bow shock position that a second component to infer the amount of dust reprocessing in the jet. Only a fraction of $\sim 0.1-0.3$ of the solar abundance of Fe and Si is in gaseous form indicating that dust still plays a major role in the depletion of refractory elements. A comparison with the SiO abundance recently derived from the analysis of submillimeter transitions shows that the Si/SiO abundance ratio is $\sim 100$, and thus, that most of the silicon released from grains by sputtering and grain–grain collisions remains in atomic form. The inferred Fe gas-phase abundance is similar to the values previously estimated in Class I jets by means of near-IR lines: this suggests that dust reprocessing does not depend on evolutionary status of the outflows although further studies are required to confirm this.

6. CONCLUSIONS

We have carried out Spitzer IRS spectroscopic observations toward the molecular jet driven by the Class 0 source L1448-C. We have detected the H$_2$ pure rotational lines from S(0) to S(7) alongside fundamental fine-structure transitions of Si$^+$, S$^0$, and Fe$^+$. Additional UKIRT/UIST spectra have been acquired, showing that, at variance with the 0–0 lines, near-IR H$_2$ vibrational line emission is mainly confined to the bow shock region where the jet and the ambient molecular cloud interact. We have analyzed these lines in order to derive the physical and dynamical parameters of the associated warm gas. The main results can be summarized as follows:

1. The detection of the fine-structure lines testifies for the presence to a previously unknown atomic jet, embedded in the molecular outflow. An analysis based on the line ratios as well as on previous observations at submillimeter wavelengths indicates that the excitation conditions of this jet are very low. In the region close to the driving source, a temperature $T_e < 1500$ K and an electron density $n_e \sim 200$–1000 cm$^{-3}$ have been measured, while the estimated ionization fraction is surprisingly $< 10^{-2}$. We suggest that the detected atomic gas represents the analog of the FEL region observed in the more evolved Class I/II sources, although with very different excitation conditions. The close similarity with the FEL region is seen in the decrease of intensity of the atomic emission with distance from the source; in both cases this is likely caused by the expansion of the jet and the consequent gas cool down. Observations with better spatial and spectral resolution, like those that will be possible with the Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope (JWST), are needed to have a better picture of the origin of this gas through comparison with jet acceleration models.

2. The $\text{H}_2$ rotational emission indicates the presence of warm gas at a temperature ranging between 600 and 900 K. It is only at the bow shock position that a second component at higher temperature is detected in the near-IR. The $\text{H}_2$ emission in the inner jet region may represent warm molecular gas enveloping the atomic gas: such a molecular component can also be related with the collimated SiO jet observed at submillimeter wavelengths, the excitation conditions of which are similar to those inferred here for the $\text{H}_2$.

3. The gas-phase abundance of Fe and Si has been estimated to infer the amount of dust reprocessing in the jet. Only a fraction of $\sim 0.1-0.3$ of the solar abundance of Fe and Si is in gaseous form indicating that dust still plays a major role in the depletion of refractory elements. A comparison with the SiO abundance recently derived from the analysis of submillimeter transitions shows that the Si/SiO abundance ratio is $\sim 100$, and thus, that most of the silicon released from grains by sputtering and grain–grain collisions remains in atomic form. The inferred Fe gas-phase abundance is similar to the values previously estimated in Class I jets by means of near-IR lines: this suggests that dust reprocessing does not depend on evolutionary status of the outflows although further studies are required to confirm this.

4. The estimates of the atomic and molecular mass flux rates have been derived from the luminosity of the outflows and the kinematical information given by submillimeter interferometric data. Values of the order of $10^{-5}$ and $10^{-7} M_\odot$ yr$^{-1}$ are inferred from the S[t]25 $\mu$m and $\text{H}_2$ line luminosities, respectively. A comparison with the momentum flux of the large-scale CO molecular outflow suggests that the detected atomic jet has the power to drive the large-scale outflow, and thus, may represent the primary jet ejected by the source.

5. At the bow shock position, the near- and mid-IR H$_2$ line observations have been compared with a C-type bow shock model. Shock velocities of $\sim 100$ km s$^{-1}$ and pre-shock densities $n$(H$_2$) $\sim 10^3$ cm$^{-3}$ can account rather well for the observed column density.

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