FIRST MEASUREMENTS OF THE ELECTRON DENSITY ENHANCEMENT EXPECTED IN C–SHOCKS.
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ABSTRACT
Magnetic precursors of C–shocks accelerate, compress and heat molecular ions, modifying the kinematics and the physical conditions of the ion fluid with respect to the neutral one. Electron densities are also expected to be significantly enhanced in shock precursors. In this Letter, we present observations of strongly polar ion and neutral molecules such as SiO, H13CO+, HN13C and H13CN, which reveal the electron density enhancements associated with the precursor of the young L1448–mm outflow. While in the ambient gas the excitation of the ions and neutrals is explained by collisional excitation by H2 with a single density of ∼106 cm−3, H13CO+ shows an over excitation in the shock precursor component that requires H2 densities of a factor of ≥10 larger than those derived from the neutral species. This over excitation in H13CO+ can be explained if we consider an additional excitation by collisions with electrons and an electron density enhancement in the precursor stage by a factor of ∼500, i.e. a fractional ionization of 5×10−5. These results show that multiline observations can be used to study the evolution of the ion and electron fluids at the first stages of the C–shock interaction.

Subject headings: stars: formation — ISM: individual (L1448) — ISM: jets and outflows — ISM: molecules

1. INTRODUCTION
In dense molecular clouds, the fractional ionization of the gas is very low (≤10−7; Guélin, Langer & Wilson 1982; Caselli et al. 1998). Electron densities are therefore insufficient to excite the first rotational levels of even strongly polar molecules like HCO+, HCN or HNC whose collisional cross sections (∼10−6–10−5 cm3 s−1; Bhattacharyya, Bhattacharyya & Narayan 1981; Saha et al. 1981; Faure & Tennyson 2001) are a factor of ≥10 larger than those of weakly polar species like CO (∼10−8 cm3 s−1; Saha et al. 1981). All attempts to use molecular excitation to measure the effects of collisional excitation by electrons in these regions have been so far unsuccessful (Langer 1985).

Modeling of the early stages of C–shocks predicts that the ion and electron densities are enhanced by the magnetic precursor (Draine 1980). For molecules like HCO+, HCN or HNC, the electron density enhancement by a factor of ∼100 produced by the precursor (see e.g. Flower et al. 1996), would make electron collisions competitive with excitation by H2 collisions for the typical densities of dark clouds (∼104 cm−3). Since the electron collisional coefficients for high initial J transitions of HCO+ are a factor of ≥10 larger than those of neutral molecules like HCN at low temperatures (∼10–20 K; Chu & Dalgarno 1974; Bhattacharyya et al. 1981), differences in the molecular excitation between ion and neutral species are therefore expected in the precursor stage 6. Toward the young L1448–mm molecular outflow, the detection of very narrow SiO emission and the enhancement of the ion abundance have been interpreted as signatures of the shock precursor (Jíménez-Serra et al. 2004). Multiline observations of strongly polar species like HCO+, HNC and HCN toward this outflow, are expected to show differences in excitation between the ambient gas where electron excitation is negligible, and the shock precursor where electron collisions should be important.

In this Letter, we present observations of several rotational transitions of SiO, H13CO+, HN13C and H13CN observed toward the ambient and shock precursor components of the L1448–mm outflow. The excitation differences observed between H13CO+, and SiO, HN13C and H13CN in the ambient and precursor components, can be explained by the electron density enhancement expected at the first stages of the C–shock evolution.

2. OBSERVATIONS & RESULTS
We observed several transitions (from J =1 to 5) of SiO, H13CO+, HN13C and H13CN toward three different positions in the L1448–mm outflow. Except the J = 4→3 lines of H13CO+, HN13C and H13CN, all the molecular transitions were observed with the IRAM 30 m telescope at Pico Veleta (Spain). We used the wobbler–switched and frequency–switched modes with position and frequency throws of 240″ and 7.2 MHz. The beam size was ∼28″, 19″ and 11″ at ∼90, 130 and 260 GHz. The SIS

6 These excitation differences between ion and neutral molecules reflect a fundamental difference between the corresponding electron–impact cross sections at low energy: for neutrals, cross sections go to zero at threshold while for ions, they are large and finite (e.g. Chu & Dalgarno 1974).
receivers were tuned to single–side band with rejections of ≥10 dB. We used the VESPA spectrometers with a spectral resolution of 40 kHz, i.e., a velocity resolution of ~0.14, 0.09 and 0.05 km s⁻¹ at ~90, 130 and 260 GHz. Typical system temperatures ranged from 100 to 500 K.

The J = 4–3 lines (~347 GHz) of H₁³CO⁺, HN¹³C and HN¹³CN were observed with the JCMT telescope at Mauna Kea (Hawaii) in the frequency–switched mode with a frequency throw of 16 MHz. The beam size was ~14′′, which matches the IRAM 30 m beam for the J = 3–2 lines of H₁³CO⁺ and HN¹³C. We used the B3 receiver in dual–mixer and single–side band mode with an image rejection of 12–14 dB. The DAS spectrometer provided a spectral resolution of 156 kHz (~0.14 km s⁻¹).

The system temperatures were of 450–560 K. All the intensities were calibrated in units of antenna temperature and converted to main beam temperatures using efficiencies of 0.82, 0.74 and 0.52 at ~90, 130 and 260 GHz for the IRAM 30 m data, and 0.63 for the JCMT data.

Fig. 1 shows the line profiles of all transitions measured toward L1448–mm (0,0), (0,–10) and (0,–20), and Tab.1 gives the observed parameters for the different velocity components. As expected for a shock tracer in the precursor (Jiménez–Serra et al. 2004), the narrow (~0.6 km s⁻¹) SiO J = 2→1 and 3→2 lines have single–peaked profiles whose peak emission is slightly redshifted (~5.2 km s⁻¹; Fig. 1) with respect to the ambient 4.7 km s⁻¹ cloud. The J = 1→0 lines of H¹³CO⁺, HN¹³C and HN¹³CN show double–gaussian profiles (the ambient and shock precursor components) and have linewidths of ~0.6–0.7 km s⁻¹ for each of the velocity components. The H¹³CO⁺ emission peaks at the shock precursor component toward the positions where narrow SiO is detected (Jiménez–Serra et al. 2004). However, the HN¹³C peak emission is centered at the ambient cloud in L1448–mm (0,0). Toward L1448–mm (0,–10) and (0,–20), the HN¹³C emission is progressively redshifted to 5.4 and 5.6 km s⁻¹, respectively (see vertical dotted lines in Fig. 1). H¹³CO⁺ and HN¹³CN also peak at 5.4 and 5.6 km s⁻¹ toward these positions, as if we were observing the evolutionary effects of the propagation of C–shocks through the unperturbed gas. The detection of broad SiO emission (terminal velocity of ~25 km s⁻¹) toward L1448–mm (0,–10) and (0,–20), supports this idea.

The J = 3→2 and 4→3 lines of H¹³CO⁺, HN¹³C and HN¹³CN tend to be single–peaked and have linewidths of ~0.7 km s⁻¹ (Tab.1). The HN¹³C emission arising from the ambient gas toward L1448–mm (0,0) is weak. However, the high–J H¹³CO⁺ emission measured toward L1448–mm (0,0) and (0,–10), is very bright and mainly arises from the precursor component. H¹³CO⁺ also shows faint emission centered at the ambient cloud toward L1448–mm (0,0). The SiO J = 5→4 and the H¹³CN J = 4→3 lines have not been detected in any of the velocity components toward L1448–mm.

3. EXCITATION DIFFERENCES BETWEEN ION AND NEUTRAL MOLECULAR SPECIES

A first look to the high–J lines of H¹³CO⁺, HN¹³C and HN¹³CN, clearly shows that the emission of H¹³CO⁺ is anomalously bright in the shock precursor component compared to that of the neutrals. Since the emission of all these species is expected to be optically thin, the line intensity ratio between different transitions is directly related to the excitation temperature of the ion and neutral fluids in the ambient and shock precursor gas. The integrated line ratios between the J = 3→2 and 1→0 lines for H¹³CO⁺ and HN¹³C, and between the J = 4→3 and 1→0 lines for H¹³CO⁺ and HN¹³CN in the ambient and precursor components, are shown in Tab.2. In the ambient cloud, the line ratios of H¹³CO⁺ are very similar to those of HN¹³C and HN¹³CN. However, the line intensity ratios of H¹³CO⁺ in the precursor component are up to a factor of 9 larger than those of the neutrals, indicating a higher excitation for the ions in this component. H¹³CO⁺ is “selectively” excited in the precursor gas.

We can estimate the H₂ densities required to explain the line intensity ratios of Tab.2, by using a model for the excitation of the observed molecules. Let us consider the LVG approximation and the only excitation by H₂ collisions. We have used the H₂ collisional rates of Turner et al. (1992) for SiO, Flower (1993) for H¹³CO⁺, and Green & Thaddeus (1974) for HN¹³C and H¹³CN.
Considering that the emissions of all molecules have similar spatial distributions, and a kinetic temperature of 21 K (see Curiel et al. 1999), the estimated H$_2$ densities and molecular column densities are shown in Tab. 3. For the ambient gas, the derived H$_2$ densities for all molecules are of few $10^3$ cm$^{-3}$, consistent with excitation by H$_2$ collisions. The H$_2$ densities derived from SiO, HN$_{13}$C and H$_{13}$CN in the precursor are similar to those of the ambient gas. However, as expected from the large H$_{13}$CO$^+$ line ratios, the H$_2$ densities required for this ion in the precursor gas are a factor of $\geq$10 larger than those for the neutral species (Tab. 3). This clearly illustrates that excitation only by H$_2$ collisions with a single density cannot explain the excitation of H$_{13}$CO$^+$ in the precursor.

4. COLLISIONAL EXCITATION BY ELECTRONS.

Since the ions have been selectively excited in the precursor component by an extra mechanism beside the H$_2$ impact, we explore the possibility that this selective excitation is produced by collisions with electrons. The efficiency of excitation of molecular ions by electrons can be significantly larger than that of neutral molecules at the low temperatures of dark clouds. To illustrate this, we compare the electron collisional rates of HCO$^+$ and HCN for the $J = 0 \rightarrow 1$ and $1 \rightarrow 2$ transitions at low and high temperatures. While the HCO$^+$/HCN collisional coefficient ratio is only $\sim$1.6 at 100 K, this ratio is increased to $\sim$6 at a temperature of 10 K (Bhattacharyya et al. 1981).

Saha et al. [1981]. This difference between the HCO$^+$ and HCN rates is expected to further increase for higher initial J and large $\Delta J$ transitions (Bhattacharyya et al. 1981). New calculations of the HCO$^+$ and H$_{13}$CO$^+$ collisional rates for all transitions between $J = 1$ and $J = 5$ (Faure & Tennyson 2000), show that the HCO$^+$ rates with $\Delta J \geq 2$ exceed those of HCN by more than one order of magnitude at 10 K. This naturally introduce a differential excitation between the ions and neutrals as observed in the precursor component.

We can constrain the electron density required to reproduce the H$_{13}$CO$^+$ line intensities observed in the precursor component by using the LVG model including collisions with both H$_2$ and electrons. For an H$_2$ density of $\sim$3 $\times$10$^3$ cm$^{-3}$ (similar to that derived from HN$_{13}$C and H$_{13}$CN; Tab 3) and a temperature of 21 K, the estimated electron densities in the precursor component toward L1448–mm (0,0) and (0,–10) in the optically thin case [N(H$_{13}$CO$^+$) $\sim$10$^{10}$ cm$^{-2}$], are $\sim$240 and 600 cm$^{-3}$ respectively, which correspond to fractional ionizations of 8 $\times$10$^{-4}$ and 2 $\times$10$^{-3}$. However, in the optically thick case [N(H$_{13}$CO$^+$) $\sim$7–9 $\times$10$^{12}$ cm$^{-2}$], and for higher temperatures ($\sim$35–45 K), the fractional ionization in the precursor decreases to $\sim$5 $\times$10$^{-5}$. Although even higher temperatures ($\sim$100 K) could reproduce the H$_{13}$CO$^+$ intensities in the precursor component for a fractional ionization of $\leq$10$^{-7}$, the derived HN$_{13}$C and H$_{13}$CN line intensities would clearly exceed (by up to a factor of 5) the upper limits of Tab. 1. The derived ionization fraction implies an electron density enhancement by a factor of $\sim$500 with respect to that of the quiescent gas ($\leq$10$^{-7}$).

Considering an extrapolation of the electron collisional rates of Saha et al. [1981] for HCN, we can now estimate the expected line intensities of HN$_{13}$C and H$_{13}$CN in the precursor for the fractional ionization ($\sim$5 $\times$10$^{-5}$) derived from H$_{13}$CO$^+$. The expected intensities are similar to those reported in Tab. 1, except for the HN$_{13}$C $J = 3 \rightarrow 2$ line whose predicted intensity exceeds the upper limits

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Line & \(V_{LSR}\) & \(\Delta v\) & T_A \(\Delta v\) & \(V_{LSR}\) & \(\Delta v\) & T_A \(\Delta v\) \\
& (km s$^{-1}$) & (km s$^{-1}$) & (K) & (km s$^{-1}$) & (km s$^{-1}$) & (K) \\
\hline
SiO(2→1) & $\sim$4.7 & $\sim$0.012 & $\sim$4.7 & 0.11(2) & 0.11(2) & 0.10(2) \\
& 5.170(8) & 0.62(2) & 0.107(5) & 5.18(3) & 0.60(8) & 0.41(8) \\
\hline
SiO(3→2) & $\sim$4.7 & $\sim$0.064 & $\sim$4.7 & 0.13(2) & 0.13(2) & 0.18(4) \\
& 5.08(7) & 0.6(2) & 0.14(1) & 5.02(6) & 0.5(1) & 0.17(3) \\
\hline
SiO(5→4) & $\sim$4.7 & $\sim$0.171 & $\sim$4.7 & 0.13(2) & 0.13(2) & 0.18(4) \\
& 5.52(7) & 0.6(2) & 0.14(1) & 5.02(6) & 0.5(1) & 0.17(3) \\
\hline
H$^{13}$CO$^+$ (1→0) & 4.584(7) & 0.59(1) & 0.629(8) & 4.685(6) & 0.70(1) & 0.62(2) \\
& 5.300(5) & 0.81(1) & 1.160(8) & 5.424(0) & 0.796(8) & 1.26(2) \\
\hline
H$^{13}$CO$^+$ (3→2) & 4.70(6) & 0.6(0) & 0.28(8) & 4.7 & 0.168 & $\sim$4.7 \\
& 5.356(6) & 0.69(2) & 2.25(8) & 5.48(2) & 0.95(5) & 0.66(8) \\
\hline
H$^{13}$CO$^+$ (4→3) & 4.70(6) & 0.55(0) & 0.08(5) & 4.7 & 0.162 & $\sim$4.7 \\
& 5.338(7) & 0.62(2) & 1.43(5) & 5.47(2) & 0.63(4) & 0.52(4) \\
\hline
HN$^{13}$C(1→0) & 4.785(3) & 0.806(7) & 0.72(1) & 4.81(2) & 0.65(2) & 0.56(2) \\
& 5.468(6) & 0.78(2) & 0.36(1) & 5.53(2) & 0.88(3) & 0.71(2) \\
\hline
HN$^{13}$C(3→2) & 4.75(5) & 0.6(1) & 0.35(4) & 4.7 & 0.261 & $\sim$4.7 \\
& 4.38(8) & 0.8(0) & 0.16(3) & 4.7 & 0.261 & $\sim$4.7 \\
\hline
HN$^{13}$C(4→3) & 4.86(5) & 1.06(7) & 0.18(2) & 4.89(2) & 0.80(6) & 0.27(1) \\
& 5.32(2) & 1.25(4) & 0.21(2) & 5.52(2) & 0.70(6) & 0.30(1) \\
\hline
\end{tabular}
\caption{Table 1}
\end{table}
in Tab. 1 by a factor of $\sim 2$. Given the uncertainties in the rates, and the relative spatial distribution of the ion and neutral gas, the data are consistent with the idea of an electron density enhancement in the precursor. High angular resolution observations are required to establish the spatial distribution of the ion and neutral species in this component.

5. ON THE ORIGIN OF THE ELECTRON DENSITY ENHANCEMENT

Toward the quiescent gas of L1448-mm, the ion and neutral fluids show similar excitation conditions. In fact, the $H_2$ densities obtained from the ions and neutrals are all consistent with few $10^5 \text{cm}^{-3}$ for this component. Since the fractional ionization is expected to be of $<10^{-7}$ in the ambient cloud (Guélin et al. 1982, Caselli et al. 1998), the high-J $H^{13}\text{CO}^+$ and $HN^{13}\text{C}$ excitation in this component is completely dominated by $H_2$ collisions.

In contrast with the quiescent gas, the precursor component shows an over excitation in $H^{13}\text{CO}^+$. The line ratios and $H_2$ densities estimated for this ion in the precursor gas, are a factor of 10 larger than those for SiO, $HN^{13}\text{C}$ and $H^{13}\text{CN}$. In section 4, we have shown that an electron density enhancement by a factor of $\sim 500$ in this component could explain the over excitation in $H^{13}\text{CO}^+$. Modeling of C-shocks shows that the UV fluorescence radiation generated by the collisional excitation of $H_2$ in the magnetic precursor rapidly enhances the ion and electron densities in this region ($t \lesssim 100 \text{ yrs}$ from the inception of the C-shock; Flower et al. 1996, Flower & Pineau des Forêts 2002). One may think that the probability to detect this enhancement toward molecular outflows for such short time-scales is negligible. However, L1448-mm is a very young outflow ($t_{\text{dyn}} \sim 1000 \text{ yrs}$), and the dynamical time-scales derived from the proper motions of the SiO bullets ($\sim 90 \text{ yrs}$; Girart & Acord 2001) are consistent with the possibility of detecting the shock precursor as predicted by C-shock models. In fact, the more redshifted velocities toward L1448-mm (0,−10) and (0,−20) are consistent with the observation of different evolutionary stages of C-shocks in the different positions in the outflow as predicted by models.

We can use our results to constrain the electron density enhancement produced by the precursor. For optically thin emission and low temperatures, the derived fractional ionization is $\sim 10^{-3}$. Flower et al. (1996) and Flower & Pineau des Forêts (2003) predicted that the ionization fraction is increased to $\sim 10^{-5}$ in the precursor stage. Our estimate of the fractional ionization clearly exceeds these results by a factor of 100, and even exceeds the cosmic abundance of atomic carbon (the main reservoir of positive charge in dark clouds; $\chi(C) \sim 2-3 \times 10^{-4}$; Cardelli et al. 1998) by a factor of $\sim 5$. However, if we increase the kinetic temperature (ions are expected to be rapidly heated by the precursor; Draine 1980) and consider optically thick emission, the ionization fraction can be decreased to $\sim 5 \times 10^{-5}$. This result is consistent with the model predictions (Flower et al. 1996, Flower & Pineau des Forêts 2003).

We cannot rule out the possibility that the ion and electron enhancement in the precursor component is produced by the radiative precursor of J-shocks (Shull & McKee 1979). Chemical models that include illumination by UV photons predict the enhancement of molecules such as HCO$^+$, HCO and HCN for $t \lesssim 300 \text{ yrs}$ (Viti & Williams 1999, Viti et al. 2003). However, HCO (a typical PDR tracer; Schenewerk et al. 1988) is not detected in the precursor component (Jiménez-Serra et al. 2004), which suggests that the ion and electron enhancements are likely due to the magnetic precursor of C-shocks.

In summary, the differences in the kinematics and excitation between the ion and neutral components in the L1448-mm molecular outflow are clear indicators of the early interaction of C-shocks with the ambient gas. The over excitation in $H^{13}\text{CO}^+$ has allowed to measure, for the first time, the electron density enhancement in the precursor of a C-shock. The estimated fractional ionization in the precursor component is $\sim 5 \times 10^{-5}$, which implies an enhancement of the electron densities by a factor of $\geq 500$ with respect to the ambient gas.

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### Table 3

| Molecule    | $H_2$ density (cm$^{-3}$) | Column density (cm$^{-2}$) |
|-------------|--------------------------|---------------------------|
| $H^{13}\text{CO}^+$ | $1.3 \times 10^5$ | $6.7 \times 10^{11}$ |
| $H^{13}\text{CN}$ | $1.9 \times 10^5$ | $1.4 \times 10^{12}$ |
| $H^{13}\text{CO}^+$ | $\leq 1.8 \times 10^6$ | $2.1 \times 10^{11}$ |
| $H^{13}\text{CO}^+$ | $\leq 1.3 \times 10^6$ | $3.0 \times 10^{11}$ |
| $H^{13}\text{CN}$ | $\leq 1.9 \times 10^6$ | $1.2 \times 10^{11}$ |
| $H^{13}\text{CN}$ | $\leq 1.6 \times 10^6$ | $1.0 \times 10^{12}$ |
| $H^{13}\text{CN}$ | $\leq 4.0 \times 10^6$ | $1.6 \times 10^{12}$ |

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