Search for anions in molecular sources: $C_4H^-$ detection in L1527*

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ABSTRACT

Aims. We present the results of a search for the negative ion $C_4H^-$ in various dark clouds, low mass star-forming regions and photon-dominated regions (PDRs). We have also searched for $C_6H^-$, $C_8H^-$ and $CN^-$ in some of the sources.

Methods. We present the results of a search for the negative ion $C_4H^-$ in various dark clouds, low mass star-forming regions and photon-dominated regions (PDRs). We have also searched for $C_6H^-$, $C_8H^-$ and $CN^-$ in some of the sources.

Results. We detect $C_4H^-$ through the $J = 9–8$ and $J = 10–9$ rotational transitions, in the low mass star-forming region L1527. We thus confirm the tentative detection of the $J = 9–8$ line recently reported toward this source. The $[C_4H^-]/[C_4H]$ ratio found is $0.011\%$, which is slightly lower than the value observed in IRC+10216, $0.024\%$, but above the $3\sigma$ upper limit we derive in TMC-1, $<0.0052\%$. We have also derived an upper limit for the $[C_4H^-]/[C_4H]$ ratio in the Horsehead Nebula, and for various anion-to-neutral ratios in the observed sources. These results are compared with recent chemical models.

Key words. astrochemistry – ISM: molecules – radio lines: ISM

1. Introduction

We have learnt that negatively charged molecules are present in the interstellar medium. Following the laboratory detection of the series of hydrocarbon anions $C_nH^-$ ($n = 1, 2, 3, 4$; McCarthy et al. 2006; Gupta et al. 2007; Brüken et al. 2007a) and of the smallest member of the isoelectronic series $C_{2n+1}^-N^+$ ($n = 0$; Gottlieb et al. 2007), astronomical searches have succeeded in detecting the three largest anions of the first series in the C-rich envelope around the evolved star IRC+10216, $C_6H^-$ and $C_8H^-$ in the dark cloud TMC-1, and $C_6H^-$ toward the low mass star-forming region L1527 (McCarthy et al. 2006; Cernicharo et al. 2007; Remijan et al. 2007; Brüken et al. 2007b; Sakai et al. 2007a). The smallest members of each series, $C_3H^-$ and $CN^-$, remain undetected in space.

It has been found that the abundance of the larger anions $C_6H^-$ and $C_8H^-$ represents a substantial fraction of that of their neutral counterparts (a few percent) while the smaller $C_4H^-$ has an abundance much lower than $C_6H_2$ ($0.024\%$ in IRC+10216). Thus, the anion-to-neutral ratio decreases when moving from large to small species. This trend was predicted many years ago by Herbst (1981), who discussed the formation and potential detectability of molecular anions in interstellar clouds. It was pointed out that the efficiency of electron radiative attachment greatly increases for species with a high electron affinity, such as the radicals $C_2H$ and $C_{2n+1}^-N$, and with a large number of vibrational states, i.e. a large size. Thus, the electron radiative attachment rate coefficients seems to be the crucial parameter controlling the anion-to-neutral ratio. Millar et al. (2007) have calculated such rate coefficients and constructed chemical models which predict anions to be abundant in dark clouds and PDRs.

To explore how ubiquitous and abundant molecular anions are in the interstellar medium we have searched for $C_6H^-$ with the IRAM-30 m telescope toward various dark clouds, low mass star-forming regions and PDRs. We have also searched for $C_8H^-$, $C_6H^-$ and $C_8H^-$ in some of the sources. In this Letter we present the results of these searches, which have led to the positive detection of $C_4H^-$ in the low mass star-forming region L1527.

2. Observations

The observations were carried out with the IRAM-30 m telescope from 24th July to 2nd August 2007. We searched for molecular anions in the starless cores: TMC-1 (at the cyanopolyyne peak), Barnard 1 (at the B1-b core) and L134N; and in the low mass star-forming regions L1527 and L483, at the position of their embedded IRAS sources. In PDRs, molecular anions are predicted to have a peak abundance in the low extinction, $A_V \sim 1.5–3$, interface where the transition of $C^+$ to CO occurs (Millar et al. 2007). We thus searched for anions toward such positions in three PDRs: the Horsehead Nebula at the so-called IR peak where the greatest hydrocarbon emission is observed (Teysier et al. 2004; Pety et al. 2005), the Orion Bar at the (CO) position where CF$^+$ was discovered (Neufeld et al. 2006), and the reflection nebula NGC 7023 at the so-called PDR peak where CO$^+$ has been observed (Fuente & Martín-Pintado 1997).

We used SIS receivers operating at 3 mm and 1 mm in single-sideband mode with image rejections $>20$ dB at 3 mm and $\geq10$ dB at 1 mm. System temperatures were 100–140 K.
Table 1. Observed line parameters.

<table>
<thead>
<tr>
<th>Source</th>
<th>Molecule</th>
<th>Transition</th>
<th>Frequency (MHz)</th>
<th>$T_A^*$ (mK)</th>
<th>$\Delta v$ (km s$^{-1}$)</th>
<th>$V_{LSR}$ (km s$^{-1}$)</th>
<th>$T_A^*$ (mK km s$^{-1}$)</th>
<th>$\eta_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMC-1$^a$</td>
<td>C$_2$H</td>
<td>$J = 9$ - $8$</td>
<td>85 634.012</td>
<td>678(12)</td>
<td>0.58(8)</td>
<td>+5.83(4)</td>
<td>417(11)</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>C$_2$H</td>
<td>$J = 9$ - $8$</td>
<td>85 672.578</td>
<td>626(11)</td>
<td>0.58(8)</td>
<td>+5.74(4)</td>
<td>386(10)</td>
<td>0.82</td>
</tr>
<tr>
<td>NGC 7023</td>
<td>C$_2$H</td>
<td>$J = 9$ - $8$</td>
<td>83 787.263</td>
<td>1.5$^a$</td>
<td>–</td>
<td>–</td>
<td>2.8$^a$</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>CN$^-$</td>
<td>$J = 2$ - $1$</td>
<td>224 525.061</td>
<td>7.8$^a$</td>
<td>–</td>
<td>–</td>
<td>14.5$^a$</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>C$_2$H$^+$</td>
<td>$J = 3$ - $2$</td>
<td>249 824.940</td>
<td>3.5$^a$</td>
<td>–</td>
<td>–</td>
<td>6.6$^a$</td>
<td>0.53</td>
</tr>
<tr>
<td>Barnard 1$^a$</td>
<td>C$_2$H</td>
<td>$J = 9$ - $8$</td>
<td>85 634.012</td>
<td>145(9)</td>
<td>1.21(7)</td>
<td>+6.79(5)</td>
<td>186(8)</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>CN$^-$</td>
<td>$J = 2$ - $1$</td>
<td>224 525.061</td>
<td>2.8$^a$</td>
<td>–</td>
<td>–</td>
<td>10.3$^a$</td>
<td>0.59</td>
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<td></td>
<td>C$_2$H$^+$</td>
<td>$J = 3$ - $2$</td>
<td>249 824.940</td>
<td>7.9$^a$</td>
<td>–</td>
<td>–</td>
<td>29$^a$</td>
<td>0.53</td>
</tr>
<tr>
<td>L134N</td>
<td>C$_2$H</td>
<td>$J = 9$ - $8$</td>
<td>83 787.263</td>
<td>1.2$^a$</td>
<td>–</td>
<td>–</td>
<td>4.4$^a$</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>CN$^-$</td>
<td>$J = 2$ - $1$</td>
<td>224 525.061</td>
<td>2.8$^a$</td>
<td>–</td>
<td>–</td>
<td>10.3$^a$</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Note: The line parameters have been obtained from Gaussian fits. Number in parentheses are 1σ uncertainties in units of the last digits. The observed positions are: TMC-1 $\alpha_{2000.0} = 0^h4^m41^s.9^a$, $\delta_{2000.0} = +25^\circ41'27''.0$; Barnard 1 $\alpha_{2000.0} = 03^h07'34''.0$; L134N $\alpha_{2000.0} = 15^h54'06''.6$, $\delta_{2000.0} = -02^\circ52'19''.1$; L1527 $\alpha_{2000.0} = 04^h39'53''.9$, $\delta_{2000.0} = +26^\circ03'11''.0$; L483 $\alpha_{2000.0} = 18^h17'29''.8$, $\delta_{2000.0} = -04^\circ39'38''.3$; Horsehead $\alpha_{2000.0} = 05^h40'53''.7$, $\delta_{2000.0} = -02^\circ28'04''.0$; Orion Bar $\alpha_{2000.0} = 05^h35'22''.8$, $\delta_{2000.0} = -05^\circ25'01''.0$; and NGC 7023 $\alpha_{2000.0} = 21^h01'32''.6$, $\delta_{2000.0} = +68^\circ10'27''.0$.

3. Results and discussion

Most of the observing time was dedicated to the search for C$_2$H$^+$ in TMC-1 and L1527, and for C$_2$H$^+$ in the Horsehead Nebula. We could only detect C$_2$H$^+$ in L1527 through the $J = 9$ - $8$ and $J = 10$ - $9$ rotational lines (shown in Fig. 1 at a spectral resolution of 40 kHz) which are observed with a signal-to-noise ratio in $T_A$ of 6 and 5 respectively. We thus confirm the tentative detection at 3 mm and 300–500 K at 1 mm. An autocorrelator was used as the back end. The spectral resolution at 3 mm was 40 kHz ($\sim 0.13$ km s$^{-1}$), except for some observations of neutral species for which 80 kHz was used (see Table 1), and 80 kHz at 1 mm ($\sim 0.10$ km s$^{-1}$). We used the frequency switching technique with a frequency throw of 7.14 MHz. Pointing and focus were checked every 1–2 h observing nearby planets or quasars. The list of observed molecules and transitions is given in Table 1.
of the $J = 9−8$ line announced by Sakai et al. (2007a). The lines have a Gaussian-like profile with a width of 0.6 km s$^{-1}$ and are centered at a source velocity of +5.85 km s$^{-1}$. Similar line properties are also found for C$_3$H (see Table 1), for C$_2$H and C$_2$H$^+$ (Sakai et al. 2007a), and for other carbon chains observed in L1527 (Sakai et al. 2007b). The rms noise levels reached in the other searches for anions, a few mK in $T_A^*$/K in most of the cases, are given in Table 1.

We have calculated beam averaged column densities (see Table 2) under the LTE approximation. In L1527, the column density of C$_3$H$^+$ is $1.6 \times 10^{10}$ cm$^{-2}$ and that of C$_3$H is $1.5 \times 10^{14}$ cm$^{-2}$. The rotational temperature ($T_{rot}$) obtained for C$_3$H is $14.1 \pm 1.6$ K, while in the case of C$_3$H$^+$ the two observed lines suggest a value of 14 K which is in agreement with that found for C$_2$H. In the rest of the cases $T_{rot}$ has been fixed; for the dense cores L1527 and L483 we assumed that $T_{rot}$ is equal to the gas kinetic temperature, 14 K and 10 K respectively (Sakai et al. 2007b; Tafalla et al. 2000), and adopted $T_{rot} = 5$ K for the cold dark clouds and $T_{rot} = 15$ K for the PDRs.
The presence of molecular anions seems to be favored in IRC +10216, where three different anions have been observed with relatively high anion-to-neutral ratios, compared to the other sources. The ratios are in particular larger in IRC +10216 than in TMC-1, most probably due to a larger ionization degree in the former.

Comparing the dense cores TMC-1 and L1527, we note that molecular anions are present at a higher level in the latter, as indicated by the larger [C\textsubscript{2}H\textsubscript{3}]\textsuperscript{-}/[C\textsubscript{2}H] and [C\textsubscript{2}H\textsubscript{4}]\textsuperscript{-}/[C\textsubscript{2}H] ratios. This has been interpreted by Sakai et al. (2007a) as due to a higher gas density in L1527 (\sim10\textsuperscript{6} cm\textsuperscript{-3}; Sakai et al. 2007b) compared to that in TMC-1 (10\textsuperscript{4} cm\textsuperscript{-3}). An increase in the gas density makes the abundance of H atoms decrease more than that of electrons\textsuperscript{1}. Thus according to Eq. (1) (the term \Gamma_{ph}/n drops for a dense cloud shielded from UV photons), this results in an increase in the anion-to-neutral-ratio which approaches its maximum value \kappa_{ea}/k_{B}, achieved in the limit when reactions with cations dominate the destruction of anions, i.e. \kappa_{ea}(B\textsuperscript{-}) \gg \kappa_{ea}(N\textsuperscript{+}) and assuming \langle B\textsuperscript{-}\rangle = [e\textsuperscript{-}].

An interesting difference between TMC-1 and L1527 is that the former is a starless quiescent core while the latter harbors an embedded protostar (IRAS 04368+2557) with an associated bipolar outflow and an infalling envelope of about 30'' (Ohashi et al. 1997). The outflow is revealed in the high velocity (~3 km s\textsuperscript{-1}) wings of some molecular lines such as HCO\textsuperscript{+} J = 1−0 (Sakai et al. 2007b). These wings are not present in the C\textsubscript{2}H\textsuperscript{-} lines, which rules out the presence of a substantial fraction of anion molecules in the outflow. The gravitational infall is indicated by the two-peak asymmetry, with a brighter blue peak, in the profiles of some optically thick lines of c-C\textsubscript{3}H\textsubscript{2} and H\textsubscript{2}CO (Myers et al. 1995). Such a profile is not visible in any of the C\textsubscript{2}H\textsuperscript{-} and C\textsubscript{2}H\textsubscript{4}\textsuperscript{-} lines observed in L1527, although they are optically thin. Small mapping observations of the in the profiles of some optically thick lines of c-C\textsubscript{3}H\textsubscript{2} and H\textsubscript{2}CO (Myers et al. 1995). Such a profile is not visible in any of the C\textsubscript{2}H\textsuperscript{-} and C\textsubscript{2}H\textsubscript{4}\textsuperscript{-} lines observed in L1527, although they are optically thin. Small mapping observations of the.


\textbf{REFERENCES}  
(1) Unpublished IRAM-30 m data; (2) Cernicharo et al. (2000); (3) Cernicharo et al. (2007); (4) Kasai et al. (2007); (5) Remijan et al. (2007); (6) This work; (7) Sakai et al. (2007b); (8) Brünken et al. (2007b); (9) Morisawa et al. (2005); (10) Dickens et al. (2000); (11) Sakai et al. (2007a).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
 & IRC +10216 & TMC-1 & Barnard 1 & L134N & L1527 & Horsehead & Orion Bar & NGC 7023 \\
\hline
[C\textsubscript{2}H\textsubscript{3}]\textsuperscript{-}/[C\textsubscript{2}H] & <0.003\textsuperscript{1,2} & <0.033\textsuperscript{6,7} & <0.048\textsuperscript{6,7} & <0.25\textsuperscript{10} & <0.003\textsuperscript{6,7} & <0.035\textsuperscript{6} \\
[C\textsubscript{2}H\textsubscript{4}]\textsuperscript{-}/[C\textsubscript{2}H] & 0.024\textsuperscript{1,1} & <0.005\textsuperscript{6,6} & <0.024\textsuperscript{6,6} & <0.062\textsuperscript{6,6} & 0.011\textsuperscript{6} & <0.033\textsuperscript{6,6} & <0.064\textsuperscript{6} \\
[C\textsubscript{2}H\textsubscript{4}]\textsuperscript{-}/[C\textsubscript{2}H] & 6.2−6.0\textsuperscript{3,4} & 1.6\textsuperscript{8} & 4.6\textsuperscript{5,6} & 9.3\textsuperscript{11} & 0.01\textsuperscript{6} & <0.20\textsuperscript{6} & <8.9\textsuperscript{3,9} \\
[C\textsubscript{2}H\textsubscript{4}]\textsuperscript{-}/[C\textsubscript{2}H] & <0.003\textsuperscript{2} & <1.0\textsuperscript{6} & <0.40\textsuperscript{6} & <6.5\textsuperscript{10} & 0.20\textsuperscript{6} & <0.20\textsuperscript{6} & <1.3\textsuperscript{6} & <0.55\textsuperscript{6} & <0.17\textsuperscript{6} & <2.6\textsuperscript{6} \\
[CN\textsuperscript{-}]/[CN] & <0.52\textsuperscript{1} & <1.9\textsuperscript{6} & <0.40\textsuperscript{6} & <6.5\textsuperscript{10} & 0.20\textsuperscript{6} & <0.20\textsuperscript{6} & <1.3\textsuperscript{6} & <0.55\textsuperscript{6} & <0.17\textsuperscript{6} & <2.6\textsuperscript{6} \\
\hline
\end{tabular}
\end{table}

1 It is predicted that in a dense cloud the abundance of H atoms varies with the gas density as the inverse while that of electrons varies only as the inverse of the square root (see e.g. Flower et al. 2007).

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