LETTER TO THE EDITOR

Astronomical identification of \( \text{CN}^- \), the smallest observed molecular anion*

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ABSTRACT

We present the first astronomical detection of a diatomic negative ion, the cyanide anion \( \text{CN}^- \), as well as quantum mechanical calculations of the excitation of this anion through collisions with para-\( \text{H}_2 \). \( \text{CN}^- \) is identified through the observation of the \( J=2-1 \) and \( J=3-2 \) rotational transitions in the C-star envelope IRC +10216 with the IRAM 30-m telescope. The U-shaped line profiles indicate that \( \text{CN}^- \), like the large anion \( \text{C}_2 \text{H}^- \), is formed in the outer regions of the envelope. Chemical and excitation model calculations suggest that this species forms from the reaction of large carbon anions with \( \text{N} \) atoms, rather than from the radiative attachment of an electron to \( \text{CN} \), as is the case for large molecular anions. The unexpectedly large abundance derived for \( \text{CN}^- \), 0.25 % relative to \( \text{CN} \), makes likely its detection in other astronomical sources. A parallel search for the small anion \( \text{C}_2 \text{H}^- \) remains so far unconvincing, despite the previous tentative identification of the \( J=1-0 \) rotational transition. The abundance of \( \text{C}_2 \text{H}^- \) in IRC +10216 is found to be vanishingly small, < 0.0014 % relative to \( \text{C}_2 \text{H} \).

Key words. astrochemistry — line: identification — molecular processes — stars: AGB and post-AGB — circumstellar matter — stars: individual (IRC +10216)

1. Introduction

The molecular anions detected so far in the interstellar and circumstellar gas are all fairly heavy linear carbon chains with three or more carbon atoms, and with neutral counterparts with large electron affinities: \( \text{C}_4 \text{H}^- \), \( \text{C}_6 \text{H}^- \), \( \text{C}_8 \text{H}^- \), \( \text{C}_6 \text{N}^- \), and \( \text{C}_6 \text{N}^- \) (McCarthy et al., 2006; Cernicharo et al., 2007; Brüken et al., 2007; Remijan et al., 2007; Thaddeus et al., 2008; Cernicharo et al., 2008). The abundance of these anions relative to the neutral counterparts increases with size and with the electron affinity of the neutral molecule, as expected for formation by radiative electron attachment (Herbst & Osamura, 2008). On inspection, however, that process fails to explain the abundance of the shortest observed anions, in particular \( \text{C}_4 \text{H}^- \) and \( \text{C}_3 \text{N}^- \). In IRC +10216, a carbon star envelope where both \( \text{C}_4 \text{H}^- \) and \( \text{C}_3 \text{N}^- \) are found, \( \text{C}_3 \text{N}^- \) has an anion-to-neutral abundance ratio about 50 times higher than that of \( \text{C}_4 \text{H}^- \), indicating that other formation processes may be at work (Cernicharo et al., 2007; Thaddeus et al., 2008; Agúndez, 2009; Cordiner & Millar, 2009). Studying the astronomical abundance of even shorter anions, in particular \( \text{C}_2 \text{H}^- \) and \( \text{CN}^- \), whose formation by radiative electron attachment is very slow, should help answer this question.

In this Letter we describe the identification in IRC +10216 of \( \text{CN}^- \) and the results on a parallel search for \( \text{C}_2 \text{H}^- \). We also present quantum mechanical calculations of the collisional excitation of \( \text{CN}^- \) by para-\( \text{H}_2 \), using the calculated rate coefficients to model the observed lines. The chemistry of \( \text{CN}^- \) in space is also briefly discussed.

2. Observations and identification of \( \text{CN}^- \)

The \( \text{C}_2 \text{H}^- \) and \( \text{CN}^- \) anions are closed-shell molecules whose rotational spectrum has been recently measured in the laboratory (Brüken et al., 2007; Gottlieb et al., 2007; Amaral, 2008). Their electric dipole moments are 3.1 and 0.65 Debye respectively (Brüken et al., 2007b; Botschwina et al., 1995).

The present astronomical observations were carried out towards IRC +10216 with the IRAM 30-m telescope on Pico Veleta (Spain). The \( J=1-0 \) rotational transition of \( \text{CN}^- \) at 112.3 GHz was observed before 2009 in the course of a \( J=3-2 \) rotational transitions of \( \text{C}_2 \text{H} \) (see Fig. 1). The \( J=2-1 \) and \( J=3-2 \) rotational transitions of \( \text{CN}^- \), at 224.5 and 336.8 GHz respectively, were observed between January and

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April 2010 with the new dual polarization EMIR receivers operating in single side band mode. The rejection of the image side band was 13–15 dB at 224 GHz and 20–30 dB at 336 GHz, depending on the polarization, as measured with strong lines. The local oscillator was shifted in frequency to identify possible contamination from the image side band. The backends were two autocorrelators with 2 MHz and 320 kHz channel spacings, respectively. The pointing and focus of the telescope were checked every 1–2 hours on Mars and on the nearby quasar 0J 287. To obtain flat baselines, the secondary mirror was wobbled by 180° at a rate of 0.5 Hz. The zenith sky opacity at 225 GHz was typically ~0.1, resulting in system temperatures of 140 K at 224 GHz and of 800 K at 336 GHz. The total integration time per polarization was 3 h at 224 GHz and 9.5 h at 336 GHz, yielding a rms noise of $T_A^* \sim 2$ mK per 2 MHz channel at both frequencies, after averaging both polarizations.

Following our initial detection in IRC +10216 of a $T_A^* \sim 3$ mK line at the frequency of the $J = 1-0$ transition of C$_2$H$^+$ (Cernicharo et al. 2008), we searched from January to April 2010 for the $J = 2-1$ transition at 166.5 GHz. The line was not detected with a $T_A^*$ rms noise level of 0.6 mK per 2 MHz channel, casting doubt on the tentative identification of the C$_2$H$^+$ $J = 1-0$ line.

The CN$^-$ observed lines are shown in Fig. 1 and the derived line parameters are given in Table I. The $J = 3-2$ transition of CN$^-$ is shown in the top panel of Fig. 1. It appears as a U-shaped line with the expected half width ($\nu_{\text{exp}} = 15 \pm 1$ km s$^{-1}$) that agrees in frequency to within 0.6 MHz with that of the CN$^-$ transition. The $J = 2-1$ transition of CN$^-$, shown in the middle panel of Fig. 1 with a spectral resolution of 2 MHz and of 320 kHz (2.7 and 0.4 km s$^{-1}$, respectively), coincides with a broad spectral feature with a complex shape that is unusual for IRC +10216, since it is neither U-shaped, flat-topped or parabolic. It is best explained as a blend, as shown in Fig. 1, that can be well fitted with two components, one U-shaped with a half width $\nu_{\text{exp}}$ of 14.5 km s$^{-1}$ centered at the frequency of the $J = 2-1$ transition of CN$^-$ (see Table I), the other with a parabolic profile, a half width $\nu_{\text{exp}}$ of 15 ± 3 km s$^{-1}$, and a rest frequency of 224518.3 ± 1.5 MHz that is close to that of the 10,9–9,8 rotational transition of SiC$_2$ in the $J = 2-1$ vibrational state (224519.7 MHz; Izuka et al. 1994). Since other $J = 2$ lines of SiC$_2$ with similar intrinsic strengths have similar shapes, half widths ($\nu_{\text{exp}} = 8-15$ km s$^{-1}$), and intensities ($T_A^* \sim 20$ mK) in our λ 0.9 mm data (Kahane et al. in preparation) as our fitted parabolic component, there is little doubt that this component comes from SiC$_2$. We note that the CN$^-$ $J = 2-1$ transition has several hyperfine components due to the nitrogen quadrupole, which can be grouped into three blocks lying at 224523.9, 224525.1, and 224527.2 MHz, with relative line strengths of 0.27, 1, and 0.12, respectively (Gottlieb et al. 2007). Due to the severe blending with the SiC$_2$ $J = 2$ and to the limited sensitivity of the astronomical observations, only the strongest hyperfine component is clearly visible in the spectrum of IRC +10216, while the middle strength component is hidden between the two stronger fitted lines (see Fig. 1), and the weakest hyperfine component lies below the noise level of the spectrum. Finally, the bottom panel of Fig. 1 shows the spectrum covering the CN$^-$ $J = 1-0$ transition, which is heavily blended with a strong line of C$_2$H. The limited spectral resolution (1 MHz) and the broadening of this CN$^-$ line by the hyperfine structure (there are three components separated by 1-2 MHz; Gottlieb et al. 2007) makes it difficult to determine the relative contributions of C$_2$H and CN$^-$ to the observed line.

There are no good candidates other than CN$^-$ for the carrier of the 336777.0 MHz line. The only plausible molecule with a transition within 2 MHz of the observed frequency, according to the line catalogs of J. Cernicharo, CDMS (Müller et al.)

### Table 1. Observed line parameters of CN$^-$

| Transition | $\nu_0$ (MHz) | $\nu_{\text{obs}}$ (MHz) | $\nu_{\text{exp}}$ (km s$^{-1}$) | $T_A^*$ (K m s$^{-1}$) |
|------------|---------------|---------------------------|-------------------------------|---------------------|
| $J = 1-0$  | 112264.8      | 112264.8                  | 14.5$^c$                      | ~ 0.07(3)$^c$       |
| $J = 2-1$  | 224525.1      | 224525.4(5)               | 14.5$^c$                      | 0.23(7)$^c$         |
| $J = 3-2$  | 336776.4      | 336776.012                | 15.0(10)                      | 0.13(2)             |

Note: $^a$ Number in parentheses are 1σ uncertainties in units of the last digit. $^b$ Frequencies derived from the rotational constants reported by Cernicharo et al. (2008). $^c$ $\nu_{\text{exp}}$ is the half width at zero level.

### Fig. 1. Spectra of IRC +10216 covering the $J = 1-0$ to $J = 3-2$ transitions of CN$^-$. Grey horizontal boxes mark their expected positions based on the laboratory frequencies and a linewidth of 29 km s$^{-1}$. Shaded areas show the fits to the line profiles obtained with the CLASS method shell. The high spectral resolution spectrum of the $J = 2-1$ line shows the expected position of the different hyperfine components with their relative intrinsic strengths. The intensity scale is expressed as $T_A^*$, antenna temperature corrected for atmospheric absorption and antenna ohmic and spillover losses. To transform into main beam brightness temperature ($T_{\text{MB}}$) in this Figure and in Table I divide by 0.78, 0.65, and 0.44 at 112, 224, and 336 GHz, respectively.
same outer envelope of IRC

file, which for a spherical expanding envelope indicates that
telescope (7" at 336 GHz). Thus CN

the emission is more extended than the half-power beam of the
source such as the outer envelope of IRC

Thaddeus et al. 2008; Cernicharo et al. 2008). A column density
lar anions observed in this source (e.g. Cernicharo et al. 2007;
not be observed from ground owing to high atmospheric opacity,
and still higher J transitions may be too weak to detect in a cool
source such as the outer envelope of IRC +10216.

The J = 3–2 line of CN, which appears free of contamina-
tion by background lines, has a pronounced U-shaped pro-
file, which for a spherical expanding envelope indicates that
the emission is more extended than the half-power beam of the
telescope (7" at 336 GHz). Thus CN appears confined to the
same outer envelope of IRC +10216, as that of other molecu-
ar anions observed in this source (e.g. Cernicharo et al. 2003
Thaddeus et al 2008; Cernicharo et al. 2008). A column density
of 5 \times 10^{12} \text{ cm}^{-2} and a rotation temperature of 16 K were de-
-derived from a rotational diagram constructed with the velocity
integrated intensities of the J = 2–1 and 3–2 lines given in Table
on the assumption of a uniform source with a radius of 20" which
is typical of molecules distributed in the outer shell. The rotation
temperature is consistent with CN emission from the cool outer
envelope. With a column density of the CN radical of 2 \times 10^{15}
\text{ cm}^{-2}, derived from several hyperfine components of the N = 1–0
and N = 3–2 transitions, we estimate a CN/CN abundance ratio of 0.25 %, which is comparable to the C_2 N^\text{+}/C N ratio in this source (0.52 %; Thaddeus et al. 2008).

From the upper limit of the J = 2–1 line of C_2 H^\text{+}, a 3 \sigma column density of < 7 \times 10^{10} \text{ cm}^{-2} was derived on the assumption of a source with a radius of 20" and a rotation temperature of 20 K. The estimated C_2 H^\text{+}/C H abundance ratio (< 0.0014 %) is at least 5 times smaller than the already small C_2 H^\text{+}/C H ratio (Agüendez 2009).

3. Modeling and discussion

To obtain a more reliable estimate of the abundance and excita-
tion conditions of CN^\text{+} in IRC +10216 we have carried out radiative transfer calculations based on the LVG formalism. The physical parameters of the envelope have been taken from Agüendez 2009. We included the first 20 rotational levels of CN^\text{+}. The rate coefficients for de-excitation by collisions with para–H_2 have been explicitly computed through quantum mechanical calculations for temperatures up to 70 K and for transitions involving the first 9 rotational levels of CN^\text{+}. The calculations are de-
scribed in the Appendix A. For collisions with He, the rate coeffi-
cients computed for para–H_2 were scaled down by a factor of 1.37 (the ratio of the square roots of the reduced mass of each couple of collision partners). For transitions involving rotational levels higher than J = 8 the Infinite Order Sudden approxima-
tion was used. As commented before, CN^\text{+} is confined to the
outer envelope of IRC +10216. We find that to reproduce the line profiles and relative intensities observed, the abundance of CN^\text{+} relative to H_2 must peak at a radius between 13" and 17" from the star. The adopted radial distribution, with a maximum abundance relative to H_2 of 2.5 \times 10^{-9} reached at a radius of 15" (12" if expressed as particle density, see grey thick line in Fig 2), produces line profiles in reasonable agreement with the observed ones (see Fig 3). We note that since the density decreases as the radius increases, the maximum in the particle density is reached at smaller radii than the maximum in the abundance relative to H_2. The total column density across the envelope (twice the radial value) is 3 \times 10^{12} \text{ cm}^{-2}, in good agreement with the value derived from the rotational diagram. In the region where most of CN^\text{+} is present (at a radius of \sim 2 \times 10^{16} \text{ cm}, where the gas ki-
netic temperature is \sim 40 \text{ K} and the density of H_2 molecules is around 4 \times 10^4 \text{ cm}^{-3} the rotational levels involved in the
CN^\text{+} observed transitions are subthermally excited. Therefore, the collision rate coefficients utilized turn out to be essential to correctly estimate the CN^\text{+} abundance in the outer layers of IRC +10216’s envelope.

To gain some insight into the formation of CN^\text{+} in the ex-
ternal layers of the molecular envelope of IRC +10216, we have performed chemical modeling calculations similar to those described by Cernicharo et al. 2008. The physical parameters of the envelope have been taken from Agüendez 2009. The rate constants and branching ratios of the reactions of anions with H, O, and N atoms, studied in the laboratory by Eichberger et al. 2007, have been updated according to

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{Abundance distribution derived for CN\textsuperscript{+} in the envelope of IRC +10216 (thick grey line labeled as "CN\textsuperscript{+} fit"), as it reproduces the CN\textsuperscript{+} observed line profiles (see Fig 3). Also shown are the abundances of CN\textsuperscript{+}, CN, and other molecular anions as calculated with the chemical model (multiplied by 0.0003, 5, 0.03, and 0.05 for CN, C_3 H^\text{+}, C_3 H\textsuperscript{+}, C_4 H^\text{+}, and C_2 N^\text{+}, respectively). The abundances are expressed as number of molecules per cubic centimeter. The angular distance is given in the top axis for an assumed distance to IRC +10216 of 120 pc.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Line profiles calculated with the LVG model (thick grey lines) using the compact CN\textsuperscript{+} abundance distribution (thick grey line in Fig 2) are compared with the observed CN\textsuperscript{+} lines (black histograms). Fits to the C_2 H and SiC\textsubscript{2} v_1 = 2 lines have been sub-
tracted in the J = 1–0 and 2–1 observed spectra. The J = 1–0 line profile is very uncertain due to the blend with the strong C_2 H line.}
\end{figure}
the values used by (Cordiner & Millar 2009) and (Walsh et al. 2009). Photodetachment rates of molecular anions have been assumed by (Millar et al. 2003) to depend on the electron affinity of the neutral counterpart. For CN− we have assumed the same rate expression adopted for C2H+, as the neutral counterparts of both molecules have similar electron affinities (3.862 and 3.809 eV respectively). Rienstra-Kiracofe et al (2002). Plotted in Fig. 2 is the calculated radial distribution of the abundance of CN− (black thin line) and of some other molecular anions. CN− is predicted to form at a much greater radius than C2H+, C2H+, C3N+, and C3N−, because, unlike the other anions, it is not formed directly from the radical CN but through the reactions of the anions C2n− (n = 5–10) with N atoms (see also (Cordiner & Millar 2009)). CN being a small molecule, the rate constant for the reaction of radiative electron attachment is likely to be very small. Here we have assumed a value of 2 × 10−15 cm3 s−1 at 300 K, similar to that computed for C2H+ by (Herbst & Osamura 2008). This process results in a too low formation rate for CN−, more than 5 orders of magnitude lower than that provided by the reactions of C2n− and N atoms. The reaction of HCN and H+ is also a source of CN− in the inner regions of the envelope, but has only a minor contribution (less than 0.2 %) to the total amount of CN− formed in the envelope. The anion C2H+ on the other hand, is solely formed through the reaction of C2H2 and H+, which takes place in the inner regions. According to our chemical model, CN− reaches a maximum abundance relative to H2 of 1.6 × 10−8 at a radius of 8 × 1016 cm, and a total column density across the envelope of 8 × 1012 cm−2. For C2H+, the model predicts a fairly small column density of 7 × 1010 cm−2, distributed over a region inner to 1016 cm. These results are in agreement with the recent chemical model of (Cordiner & Millar 2009), who predicted that both CN− and C2H+ could be detected in the circumstellar envelope of IRC +10216.

The abundance and column density predicted for CN− by the chemical model is in reasonable agreement with the value derived from the observed lines and the LVG model. However, the calculated spatial distribution is markedly different from that derived by the observations (see Fig. 2). In fact, by adopting the CN− abundance distribution obtained with the chemical model the resulting line profiles show important discrepancies as compared with the observed ones. While the calculated absolute line intensities are about the same order of magnitude as those observed, significant disagreements between the relative intensities and the line profiles are found. The calculated line intensity decreases too rapidly when going from the J = 1–0 to the J = 3–2, and the computed line profiles are too much U-shaped, with nearly all the emission predicted to occur at the line edges (i.e. at the terminal expansion velocity). These discrepancies arise because the chemical model predicts that CN− is present in a region of the circumstellar envelope that is too far from the central star. An abundance distribution more compact than predicted by our chemical model may arise if the envelope is not modeled as being smooth, but as having density-enhanced shells. (Cordiner & Millar 2009) have recently studied the effect of such density enhancements on the radial distribution of molecular abundances and found that molecules formed in the outer envelope would concentrate at the position of the first and/or second shells, located at 15 and 27″ respectively. For C2H+ the chemical model predicts it to be distributed over an 8″ diameter region (see Fig. 2) with a total column density of 7 × 1010 cm−2. Once averaged over the 14.6″ beam of the IRAM 30-m telescope at the frequency of the J = 2–1 transition, the calculated column density is about 3 times lower than, and thus consistent with, the 3σ upper limit derived from the non detection of the J = 2–1 line.

The identification of CN− in IRC +10216 with a relatively large anion-to-neutral abundance ratio (0.25 %) suggests that it may be detectable in other astronomical sources. Upper limits to the CN−/CN+ abundance ratio as low as 0.2–2 % were obtained in TMC-1, L1527, Barnard 1, and the Orion Bar in a previous search for the J = 2–1 transition by (Agúndez et al. 2008). More sensitive observations would be needed if the abundance of CN− in other sources is similar to that found in IRC +10216.

The high abundance of CN− compared to that of C2H+ demonstrates the efficiency of the reactions of N atoms and large carbon anions. A more sensitive search for C2H+ might support this alternate scheme for the formation of anions in space, and perhaps explain the low observed abundance of C2H+ as compared to C3N−.

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1 http://www.physics.ohio-state.edu/~eric/research.html
Appendix A: CN$^-$−H$_2$ collision rate coefficients

The potential energy surface (PES) of the CN$^-$−H$_2$ complex was calculated ab initio using single and double-excitation coupled cluster method with non-iterative triple excitations [CCSD(T)] (Knowles et al. 1993, 2000) implemented in MOLPRO\footnote{MOLPRO, version 2006.1, a package of ab initio programs, H.-J. Werner, P. J. Knowles, R. Lindh, F. R. Manby, M. Schütz, P. Celani, T. Korona, G. Rauhut, R. D. Amos, A. Bernhardsson, A. Berning, D. L. Cooper, M. J. O. Deegan, A. J. Dobbyn, F. Eckert, C. Hampel and G. Hetzer, A. W. Lloyd, S. J. McNicholas, W. Meyer and M. E. Mura, A. Nicklass, P. Palmieri, R. Pitzer, U. Schumann, H. Stoll, A. J. Stone, R. Tarro and T. Thorsteinsson, see http://www.molpro.net}.

The geometry of the system was described in the body-fixed frame and characterized by three angles ($\theta, \theta', \phi$) and the distance $R$ between the centers of mass of H$_2$ and CN$^-$. The H$_2$ bond distance was fixed at $r_0=1.44876$ a$_0$ and the CN$^-$ bond distance was varied for the purpose of the averaging of the PES over the lowest vibrational state of the CN$^-$ diatom. The basis set superposition error correction counterpoise procedure of Boys & Bernardi (1970) was applied. The four atoms were described by the correlation-consistent triple zeta basis set (aug-cc-pVTZ) of Woon & Dunning (1994), augmented by the (3s, 2p, 1d) midbond functions defined by Williams et al. (1995), placed at mid-distance between the CN$^-$ and H$_2$ centers of mass. The final $V(r, R, \theta, \theta', \phi)$ PES is five-dimensional, however, in this work we included only three perpendicular orientations of the H$_2$ molecule [$\theta, \theta'$, pairs: (0, 0), (0, 90), (90, 90)] to average over H$_2$ rotations. Additionally, the PES was averaged over the CN$^-$ internuclear distance corresponding to the CN$^-$ vibrational ground state wave function. The 2-D PES was finally obtained as an arithmetic average of three H$_2$ orientations. The full five-dimensional PES and four-dimensional scattering calculations will be presented elsewhere.

We considered collisions of CN$^-$ with para–H$_2$(j$_2=0$) at low temperatures. The rotational levels of CN$^-$ and H$_2$ are designated by $j_1$ and $j_2$, respectively. We used the fully quantum close-coupling approach of Arthurs & Daigle (1960). The standard time-independent coupled angular-momentum equations were solved using the MOLSCAT code (Hutson & Green, 1994).

Calculations were carried out at values of the total energy ranging from 3.6 to 500 cm$^{-1}$. The integration parameters were chosen to ensure convergence of the cross sections over this range. At the largest total energy considered (500 cm$^{-1}$) the CN$^-$ rotational basis included channels up to $j_1 = 21$ to ensure convergence of the excitation functions $\sigma_{j_1,j_2\rightarrow j'_1,j'_2}(E)$ for transitions including up to the $j_1 = 8$ rotational level of CN$^-$. The rotational basis of H$_2$ was restricted to $j_2 = 0$ levels. The coupling with the $j_2 > 2$ (and higher) states of H$_2$ was not taken into account. As shown by Lique et al. (2008), this approach is expected to yield reliable results for the energy range considered here. From the above described excitation functions one can obtain the corresponding state-resolved thermal rate coefficients by Boltzmann averaging:

$$k_{j_1,j_2\rightarrow j'_1,j'_2}(T) = \left( \frac{8}{\pi \hbar^3 k T} \right)^{1/2} \times \int_0^\infty \sigma_{j_1,j_2\rightarrow j'_1,j'_2} E e^{-E/kT} dE$$  \hspace{1cm} (A.1)

where $k$ is the Boltzmann constant. To obtain precise values of the rate constants, the energy grid was chosen to be sufficiently fine to include the numerous scattering resonances. The total energy range considered in this work allows us to determine rate coefficients up to 70 K. The temperature dependence of the rate coefficients for selected de-excitation transitions is illustrated in Fig. A.1 with the values given in Table A.1.

![Fig. A.1. Collisional de-excitation rate coefficients of CN$^-$ by collisions with para–H$_2$ shown as a function of temperature for the $J=1\rightarrow0$, 2\textendash 1, 2\textendash 0, and 3\textendash 1 rotational transitions of CN$^-$](image_url)

| Transition | Temperature (K) |
|------------|-----------------|
| 1 → 0      | 10  | 20  | 30  | 40  | 50  | 60  | 70  |
|            | 3.33 | 3.06 | 2.88 | 2.72 | 2.59 | 2.48 | 2.39 |
| 2 → 0      | 0.81 | 0.65 | 0.59 | 0.55 | 0.54 | 0.53 | 0.53 |
| 2 → 1      | 4.81 | 4.50 | 4.25 | 4.05 | 3.88 | 3.74 | 3.62 |
| 3 → 0      | 0.67 | 0.64 | 0.61 | 0.59 | 0.57 | 0.56 | 0.52 |
| 3 → 1      | 1.32 | 1.18 | 1.07 | 1.00 | 0.96 | 0.93 | 0.92 |
| 3 → 2      | 4.81 | 4.62 | 4.39 | 4.19 | 4.03 | 3.88 | 3.77 |

Table A.1. CN$^-$–H$_2$ collision rate coefficients (10$^{-10}$ cm$^3$ s$^{-1}$)

Note: The complete set of de-excitation rate coefficients of CN$^-$ by collisions with para–H$_2$ considered in this study is available on the BASECOL website http://basecol.obspm.fr/