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LETTER

Letter to the Editor

Observation of DCO^+ in the Large Magellanic Cloud

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Abstract. We report on the detection of DCO^+ and, tentatively, DCN in their rotational J=2–1 transitions towards the N159 region in the Large Magellanic Cloud (LMC). These detections of deuterated molecules in an extragalactic source complement those already published by Chin et al. (1996). The resulting estimate of the HCO^+/DCO^+ abundance ratio is 120^{+60}_{-60} (total 2σ uncertainties). Assuming a Galactic D/H ratio for the LMC leads to an estimate of the kinetic temperature of the molecular gas and an upper limit to the fractional electron abundance of 10–27 K and a few$\times 10^{-5}$, respectively. The temperature estimate is in accordance with excitation calculations using a number of other molecules. The HCO^+/DCO^+ abundance ratio in N159 is a factor of a few higher than in cores of Galactic molecular clouds. This is probably due to a somewhat higher gas temperature and possibly a considerably higher electron abundance in N159. The estimated HCN/DCN abundance ratio is 60^{+50}_{-35} (total 2σ uncertainties).

Key words: ISM:molecules – Galaxies:abundances – Galaxies:ISM – Magellanic Clouds – Radio lines:galaxies – Radio lines:ISM

1. Introduction

The first detection of the deuterated formyl ion, DCO^+, in the Galactic interstellar medium (ISM) was reported by Hollis et al. (1976). Now, twenty years later, we report on the detection of DCO^+ in an external galaxy, the Large Magellanic Cloud (LMC). We also present a tentative detection of DCN in the LMC. DCN was found in the Galaxy by Jefferts et al. (1973). Deuterated molecules emitting at radio wavelengths are important for the study of the physics and chemistry of molecular clouds. Since chemical fractionation often takes place at the relatively low kinetic temperatures of the molecular gas and considerably changes the D/H ratio for isotopomer pairs in favour of the deuterated isotopomer, they serve as important tests of gas-phase ion-molecule chemistry.

The kinetic temperature, as well as the abundances of electrons and neutral trace molecules (CO, H_2O, N_2, ...) are important factors involved in the fractionation of deuterium. Thus it is possible to estimate an upper limit for each of these three quantities if the level of fractionation is known.

The electron density is of importance in the evolution of a molecular cloud through its coupling to the magnetic field, thereby supporting the cloud (or parts of it) against a gravitational contraction. Furthermore, if the fractional electron abundance is high ($\gtrsim 10^{-5}$), the contribution of electron collisions to the excitation of molecules has to be taken into account when deriving the physical conditions of the gas using excitation and radiative transfer models. The possibility to use deuterated molecules as indicators of the electron density has been debated quite a lot during the last twenty years and the magnitude of the main actor on the scene, viz. the rate coefficient of dissociative electron recombination of H_3^+, $\alpha(H_3^+)$, has been changing with several orders of magnitude in the meantime. Recent laboratory measurements (Sundström et al. 1994 and references therein; see also Larsson et al. 1996) point towards a fairly high value for $\alpha(H_3^+)$ ($\approx 10^{-7}$ cm^3 s^{-1}) making the HCO^+/DCO^+ abundance ratio again interesting as a probe of the fractional electron abundance in the molecular gas.

Comprehensive chemical models of interstellar molecular clouds, including deuterated molecules, have been developed by Brown & Rice (1981, 1986), Brown & Millar (1989), and Millar et al. (1989). The potential importance of including atomic H and D besides H_2 and HD in the reactions was pointed out in the theoretical work by Dalgarno & Lepp (1984) and it was subsequently confirmed in laboratory measurements by Adams & Smith (1985).

Observational studies of DCO^+ in Galactic molecular clouds have been published by e.g. Guélin et al. (1977, 1982), Langer et al. (1978), Wootten et al. (1982), Loren et al. (1990), and Butner et al. (1995). The detection of deuterated molecules in external galaxies opens new doors for extragalactic chemistry.

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In this context the Magellanic Clouds are of special interest due to their proximity and by providing the molecular gas with an environment which differs considerably from that in the Milky Way.

During the preparation of this manuscript we have become aware of independent detections of DCO^+ (three sources) and DCN (one source) in the LMC by Chin et al. (1996). In contrast to the present paper, Chin et al. focus on the cosmologically interesting D/H ratio. They find a ratio consistent with that observed in the Galaxy, provided that the kinetic temperature is about 20 K.

2. Observations

The observations were carried out in December 1995 with the Swedish–ESO Submillimetre Telescope (SEST)[1] at La Silla, Chile. The receiver system consisted of a cryogenic SIS mixer, operating in the 2 mm band, tuned to single sideband mode (resulting system temperatures, corrected for the atmosphere, were typically 175 K), connected to a low resolution acousto-optical spectrometer (1440 channels, total bandwidth of 1 GHz). Dual beam-switching, with a beam-throw of $\approx 12'$ in azimuth, was used as observing mode. The intensity calibration was done with the chopper-wheel method. Pointing and focus checks were made towards the stellar SiO maser R Dor, located about 20° from the source position [N159, α=05^{h}40^{m}03.0^s, δ=−69°47′03″ (B1950)]. The pointing offsets were typically 3″ r.m.s. in each coordinate, leading to a radial pointing error distribution which peaks at $\sqrt{2} \times 3''$. For a point source this corresponds to an intensity error (2σ) of +15 % at 144 GHz (beam size $\approx 35''$). Calibration uncertainties are estimated to be $\pm$15%. Thus, the intensity error caused by pointing and calibration uncertainties amounts to $^{+21}_{-15}$%. The total uncertainty in the observed intensities is then obtained by adding quadratically the contribution of noise in the spectra to the calibration and pointing uncertainties.

3. Results

The observational results, together with the estimated column densities are summarized in Table 1. The line parameters are from fits of Gaussian profiles to the measured spectra. For completeness, we have included HCO^+, $H^{13}CO^+$, and HCN data from Johansson et al. (1994). The brightness temperatures are given in the main-beam brightness temperature scale [$T_{\rm mb} = T_{\rm A}^*/\eta_{\rm mb}$, where $T_{\rm A}^*$ is the Rayleigh-Jeans antenna temperature above the atmosphere and $\eta_{\rm mb}$ is the main-beam efficiency (0.65 at 144 GHz)]. The given uncertainties in the integrated intensities are defined by 2σ noise fluctuations in the spectra. The DCO^+(J=2–1) and DCN(J=2–1) spectra are shown in Fig. 1. A first order baseline has been subtracted from the spectra. The channel width is $\approx 1.4\,{\rm km\,s^{-1}}$. The velocities in the spectra are relative to the local standard of rest (LSR).

[1] The Swedish–ESO Submillimetre Telescope is operated jointly by ESO and the Swedish National Facility for Radio Astronomy, Onsala Space Observatory, at Chalmers University of Technology.

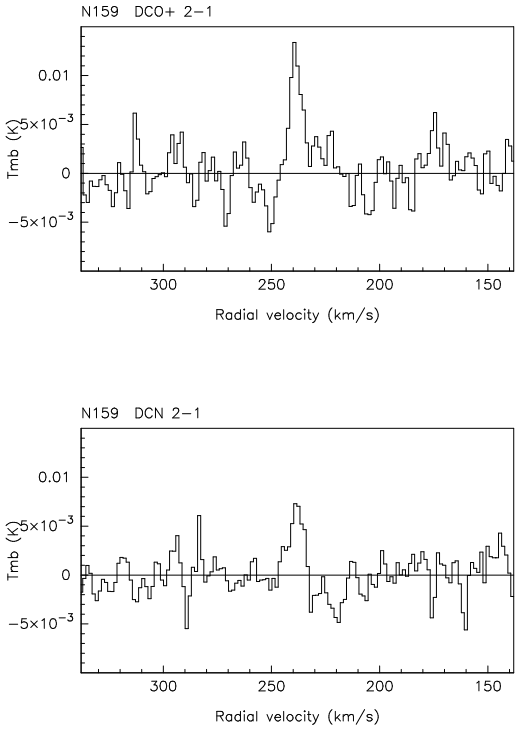

Fig. 1. The observed spectra of DCO^+ and DCN towards N159.

3.1. Column densities

We have derived column density estimates using two methods: i) rotation diagram analysis (denoted ROT), and ii) statistical equilibrium excitation and radiative transfer calculations (denoted MEP). In the following analysis we mainly use velocity integrated line intensities $I = \int T_{\rm R} dv$, which have been corrected for beam-dilution and finite source size. The correction has been carried out by assuming that the source distribution on the sky is Gaussian with a FWHM diameter ($\Theta_{\rm source}$) of 40″ [estimated from maps of different molecules (Johansson et al. 1994; Heikkilä et al. 1997)], i.e. , $I = I_{\rm mb}/\eta_{\rm bf}$ where $\eta_{\rm bf}$= $\Theta^2_{\rm source}/(\Theta^2_{\rm mb} + \Theta^2_{\rm source})$ is the Gaussian beam-filling factor. The presented column density estimates are peak values (possible small-scale beam-filling is not taken into account). Conversion to beam-averaged quantities is obtained by multiplication by $\eta_{\rm bf}$. The solutions are constrained by total observational (2σ) uncertainties as described in Sect. 2.

In the following we assume optically thin emission, in agreement with all existing mm-wavelength data of isotopic intensity ratios observed in the LMC, including the $HCO^+/H^{13}CO^+$ ratio (Johansson et al. 1994).

3.1.1. Rotation diagram method

We use the standard rotation diagram method (see e.g. Linke et al. 1973; Cummins et al. 1986), which assumes optically thin emission and uniformly excited rotational levels. The same value for the electric dipole moment is used for the deuterated and the non-deuterated species (3.91 Debye for HCO^+ and

Table 1. Line parameters and estimated column densities

Molecule	Transition	T_{mb} (K)	v_{LSR} (km s^{-1})	Δv (km s^{-1})	I_{mb} (K km s^{-1})	N_{ROT} (cm^{-2})	N_{MEP} (cm^{-2})
DCO^+	J=2–1	0.0125	238.7	6.5	0.087 (0.017)	(1.1-2.0)$\times10^{11}$	(0.84-2.5)$\times10^{11}$
DCN	J=2–1	0.0069	238.5	7.9	0.058 (0.013)	(1.2-2.3)$\times10^{11}$	(0.25-1.2)$\times10^{12}$
HCO^+	J=1–0	0.61	237.7	7.3	4.72 (0.26)	(1.3-1.8)$\times10^{13}$	(1.0-2.0)$\times10^{13}$
$H^{13}CO^+$	J=1–0	0.018	237.2	5.2	0.098 (0.020)	(2.6-4.3)$\times10^{11}$	(1.9-3.6)$\times10^{11}$
HCN	J=1–0	0.20	239.2	10.3	2.14 (0.17)	(1.0-1.4)$\times10^{13}$	(1.2-4.8)$\times10^{13}$

2.98 Debye for HCN). Since we have data for only one transition for DCO^+, $H^{13}CO^+$, HCN and DCN, we use for these species the same excitation temperature as for HCO^+ ($\approx$6 K, cf. Johansson et al. 1994). The resulting column density ratio estimate for HCO^+/DCO^+ is 100^{+50}_{-32}. The $H^{13}CO^+$(J=1–0) line together with a $^{12}C/^{13}C$ ratio of 50^{+25}_{-20} (cf. Johansson et al. 1994) yields 112^{+57}_{-45}. The HCN/DCN ratio is 69^{+39}_{-23}. The MEP analysis indicates T_{ex}=4 K for HCN, which gives a somewhat lower HCN/DCN ratio of 45^{+26}_{-15} assuming uniform excitation.

3.1.2. Excitation and radiative transfer analysis

The statistical equilibrium excitation calculations incorporate the first twelve rotational levels in the lowest vibrational state. We have used the same collision coefficients for the deuterated and the main isotopomers [H_2– HCO^+ system from Green (1975), and Monteiro (1985); He–HCN system from Green & Thaddeus (1974)]. The radiative transfer is treated in the mean escape probability approximation (MEP). The model cloud is spherical and has a constant density and temperature. The column densities were determined by fitting the excitation and radiative transfer model to the observed peak brightness temperatures $T_R = T_{mb}/\eta_{bf}$. As input data we used estimates of the kinetic temperature [T_k=20 $\pm$10 K] and the number density of molecular hydrogen [$n(H_2)$=(5–100)$\times10^4$ cm^{-3}] derived from a multi-transition study of several other molecules detected in N159 (Heikkilä et al. 1997).

The resulting HCO^+/DCO^+ and HCN/DCN column density ratios are 120^{+60}_{-60} and 50^{+25}_{-25}, respectively.

3.2. Kinetic temperature

Our main interest in the present work is to use the HCO^+/DCO^+ abundance ratio as a thermometer and to compare this estimate of the kinetic temperature of the molecular gas with results using other techniques. The strongly temperature dependent chemical fractionation of deuterium enhances the abundance of deuterated molecules by a large factor over the cosmic deuterium-to-hydrogen ratio, implying that the estimate of the kinetic temperature is rather insensitive to the adopted D/H ratio. A key reaction in the formation of DCO^+ is

$$H_3^+ + HD \rightleftharpoons H_2D^+ + H_2 + \Delta E \quad (1)$$

The rate coefficient for the reverse reaction is reduced by a factor $\sim e^{-\Delta E/kT}$ [ΔE/k is temperature dependent, taking values between 130 and 240 K, see e.g. Watson (1976, 1977); Herbst (1982); Smith et al. (1982)], due to the energy difference between the reactants and the products.

Using Fig.1 and Eq.(12) from Herbst (1982) the kinetic temperature can be estimated from the expression $T_k \approx 227/\ln[(30X(DCO^+))/(X(HD)X(HCO^+))]$, where X(mol) is the fractional abundance of the molecule in question relative to molecular hydrogen. Using the Galactic D/H ratio, $\approx1.7\times10^{-5}$ (Linsky et al. 1995), $X(HD)\approx3.4\times10^{-5}$ yields $T_k \approx$ 23–27 K. Millar et al. (1989) studied the deuterium chemistry for a model cloud with $n(H_2)=10^4$ cm^{-3} and A_V=10 mag by running a comprehensive pseudo-time-dependent chemical model. By using the abundance ratios from their Tables 2 and 3 we obtain a kinetic temperature estimate of 11–24 K. Our estimate of the number density of molecular hydrogen (few$\times10^5$ cm^{-3}) is about one order of magnitude higher than the value in the Millar et al. (1989) model and this, together with the lower elemental abundances in the LMC, may affect the results of the chemical model and lead to some change in the abundances and accordingly to the temperature estimates.

3.3. Fractional electron abundance

We estimate an upper limit to the fractional electron abundance, X(e), using two different methods. The first method, introduced by Watson (1976, 1977), makes use of the HCO^+/DCO^+ abundance ratio as a measure of the H_3^+/H_2D^+ ratio and balances the production and destruction rates of H_2D^+ (via deuteration of H_3^+ and dissociative electron recombination, respectively). The second method (Wootten et al. 1979) involves the fractional abundance of HCO^+ and CO together with the ionisation rate of H_2 (ζ). In the latter method the production (by reaction between H_3^+ and CO) and destruction of HCO^+ (dissociative electron recombination) are balanced.

Using the following values for the quantities in question, $X(HD) \approx 3.4\times10^{-5}$, $k(H_3^+ \rightarrow H_2D^+) \approx 1.7\times10^{-9}$ cm^{3}s^{-1}, $\alpha(H_2D^+) \approx 3.5\times10^{-7}$ cm^3 s^{-1} together with the observed HCO^+/DCO^+ abundance ratio, method 1 gives $X(e)<1\times10^{-5}$. Method 2 yields $X(e)<(0.4–4)\times10^{-7}$ if $\zeta=10^{-17}$–10^{-15} s^{-1}, $n(H_2) \approx 10^5$ cm^{-3}, $X(HCO^+) \approx 2.5\times10^{-10}$, $X(CO) \approx 2.5\times10^{-6}$, $\alpha(HCO^+) \approx 2.4\times10^{-6}$ cm^3 s^{-1}, $\alpha(H_3^+) \approx 6.7\times10^{-7}$

$cm^3\ s^{-1}$ and $k(H_3^+ \rightarrow HCO^+) \approx 1.8\times10^{-9}\ cm^3\ s^{-1}$. The reaction rate coefficients used are in both methods those at T_k=20 K, calculated from formulas taken from Sundström et al. (1994), Larsson et al. (1996) and de Boisanger et al. (1996).

4. Discussion

In order to put the above derived numbers in a context, we have compared HCO^+, $H^{13}CO^+$ and DCO^+ column densities and integrated intensity ratios (corrected for beam and source sizes) in N159 with published data from studies of Galactic molecular clouds (Guélin et al. 1982; Loren et al. 1990; Butner et al. 1995). We find that the $H^{13}CO^+/DCO^+$ intensity ratio is typically a factor of two lower in Galactic clouds. The HCO^+/DCO^+ column density ratio shows a similar trend (although the scatter is large). These differences may be explained by the fact that the Galactic clouds in the above quoted studies are mainly cold cores or dark clouds with no or little star-formation activity in contrast to the N159 cloud. Thus, it is reasonable that the gas in N159 is warmer and has a higher electron abundance, both properties resulting in higher HCO^+/DCO^+ ratios.

While our estimate of the kinetic temperature (based on deuterium fractionation) agrees well with the MEP results of other molecules, the two methods used here to estimate fractional electron abundances yield very different results. Deuterium fractionation gives $X(e)<1\times10^{-5}$ while formation-destruction balance of HCO^+ points towards a much lower upper limit (few$\times10^{-7}$). Both estimates suffer from uncertainties in the reaction rates for dissociative electron recombination and the adoption of a very simplistic view of the chemical reactions involved. On top of this, the latter method uses the production rate of H_3^+ via cosmic ray/photo ionisation of H_2, ζ, as a free parameter. ζ approaching $10^{-12}\ s^{-1}$ would be needed to reach $X(e) \approx 10^{-5}$.

Support for a high $X(e)$ comes from a recent study of C^+ by Israël et al. (1996). If we use their values for the PDR-parameters with their Eq.(8), we find $X(e)\approx10^{-6}$–10^{-5} for the PDR-component of the gas. Bearing in mind the low dust-to-gas ratio, a strong UV radiation field and, presumably, a high degree of clumpiness of the molecular gas, it is not unreasonable that the abundance of electrons is high in the LMC. Also the correlation between C^+/CO and HCO^+/CO intensity ratios (Johansson et al. 1997) suggests a connection between C^+ and HCO^+.

Since the DCN detection is only tentative [although it is supported by the detection of DCN in N113 by Chin et al. (1996)], we only note here that the resulting HCN/DCN column density ratio seems to be somewhat lower than that of HCO^+/DCO^+. A possible implication of this is that the HCN and DCN emissions originate from the (colder/less ionised) interiors of the clumps while that of HCO^+ to a higher degree comes from the surfaces.

The data of Chin et al. (1996) indicates a variation of the HCO^+/DCO^+ ratio within the LMC. Correcting for the different beam sizes at 3 mm and 2 mm [using the source sizes from Chin et al. (1997)] we arrive at (nominal) abundance ratios of 23 and 28 for the regions N113 and N44BC. Such ratios yield kinetic temperatures and upper limits for $X(e)$ [method 1] of $\approx$ 20 K [in agreement with Chin et al. (1996)] and 2×10^{-6} for N113 and N44BC. $X(e)$ is a factor of 5 lower than in N159. If this difference is significant, it could indicate that the N159 region is in a more active phase of star formation than N113 and N44BC, leading to an enhanced level of ionisation.

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