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OBSERVATIONS OF DCO^+: THE ELECTRON ABUNDANCE IN DARK CLOUDS

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ABSTRACT

The $J = 2\text{–}1$ rotational line of DCO^+ has been definitely detected in five molecular clouds, including three dark clouds, L63, L134, and L134 N, and marginally detected in four others. The DCO^+ emission has been mapped in L134 N and extends over a region of 3′. The DCO^+/HCO^+ abundance ratio found at the centers of dark clouds is large and implies a fractional electron abundance of less than 10^{-8}. This low electron density sets constraints on the metals and possibly CO as well as on the hydrogen density.

Subject headings: deuterium — interstellar: abundances — interstellar: molecules

Despite the major role played by electrons and ions in both interstellar chemistry and the dynamics of the interstellar gas, very little is actually known about the state of ionization in the dense molecular clouds. Observations of the cooling of the 6 cm line of formaldehyde show only that the fractional abundance of electrons, $x_e = n(e)/n(H_2)$, is lower than 10^{-5} in most of these regions; the HCO^+ and N_2H^+ observations, on the other hand, indicate that x_e is larger than 10^{-9} in most molecular clouds.

A new and very sensitive way to estimate the electron density in cold clouds is provided by the study of the DCN/HCN or DCO^+/HCO^+ abundance ratio; this approach is suggested by the analysis of deuterium enhancement processes in interstellar molecules (Watson 1976, 1977). Deuterium enhancement in molecules is a relatively slow process which has to compete with electron recombination; the unexpectedly large amounts of DCN and DCO^+ observed in some interstellar clouds imply an extremely small rate of electron recombination, setting a very low limit on the electron density. This limit depends only on the ratio of two well-known reaction rates. While both HCN and HCO^+ are widely distributed and easy to observe, HCO^+ is a better probe of cloud conditions, since its formation by gas-phase reactions is straightforward and seems better understood.

Recently, Hollis *et al.* (1976) have reported the detection of the $J = 1\text{–}0$ rotational line of DCO^+ in three interstellar sources, including the dark cloud L134. In this *Letter* we report the observation of the $J = 2\text{–}1$ DCO^+ line in several sources. Our observations confirm the discovery of interstellar DCO^+ by Hollis *et al.*, and show that over a sizable region at the center of three dark clouds, the DCO^+/HCO^+ abundance ratio is commonly enhanced by a factor of $\sim 10^5$ with respect to the cosmic ratio of D/H. As will be shown, this enhancement implies that $x_e \lesssim 10^{-8}$.

Observations were carried out in 1976 October and December and 1977 January, with the 5 m telescope of the Millimeter Wave Observatory, Ft. Davis, Texas.[1] At the frequency of the $J = 2\text{–}1$ rotational line of DCO^+ (144,077.3 MHz), the half-power beamwidth of the telescope is 1′.8 and the 250 kHz width of one of the 40 channels corresponds to 0.52 km s^{-1}. At the frequency of the 1–0 HCO^+ line (89,188.6 MHz) these values are 3′.0 and 0.84 km s^{-1}, respectively. In order to discriminate against spurious signals, the local oscillator frequency was switched between four reference frequencies, thus making every radio-frequency spectral feature appear at four different parts of the filterbank.

We have searched for the HCO^+ ($J = 1\text{–}0$) and the DCO^+ ($J = 2\text{–}1$) lines in 19 molecular clouds (25 positions altogether). HCO^+ has been observed in all but one of these clouds. DCO^+ has been detected in five clouds (eight positions) with a peak signal larger than 3 times the rms noise level in one channel (cf. Fig. 1); in view of the width of the lines (at least two channels) we consider these to be definite detections; we find it significant also that three of these five DCO^+ sources are cool dark clouds, exhibiting only weak HCO^+ emission. Peak signals larger than two times the rms noise level have been observed in four additional clouds. A crude 9-point map of the DCO^+ and HCO^+ emission has been made in the dark cloud L134 N. DCO^+ and HCO^+ are observed right at the center of the highly

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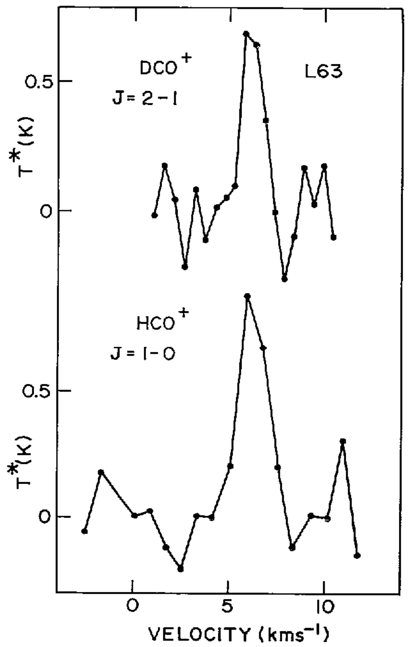

FIG. 1.—Typical DCO^+ and HCO^+ spectra observed in a dark cloud

obscured part of this cloud ($A_v \approx 7$ mag.) and extend over a region $\sim 3'$ wide (about 0.1 pc). These observational results are summarized in Table 1.

Lower limits to the abundance ratio $R = x(DCO^+)/x(HCO^+)$ can be directly derived from the data of Table 1 if we assume that (1) the HCO^+ and DCO^+ sources extend uniformly over the main beam of the antenna; (2) both observed lines are optically thin; (3) the excitation temperature of the $J = 2$–1 line of DCO^+ is approximately equal to that of the $J = 1$–0 line of HCO^+; and (4) both excitation temperatures are smaller than the radiation temperature observed for the $J = 1$–0 line of CO, T*(CO). Under these conditions, we have:

$$R > \frac{T^*(DCO^+, J = 2\text{–}1)}{T^*(HCO^+, J = 1\text{–}0)} 0.5 \exp\,[6.1/T^*(CO)]\,, \tag{1}$$

where T^* denotes the beam-averaged radiation temperature. Limits to R derived by this way are listed in Table 1.

It should be noted that, at least in the case of the three dark clouds, none of the above assumptions leads to an overestimate of R by a factor larger than 2. The use of beam-averaged temperatures instead of the true radiation temperature cannot affect the limits in Table 1 greatly, since the HCO^+ emission region is at least as extended as that of DCO^+. Also, it may be shown, following the arguments of Goldreich and Kwan (1974), that because the DCO^+ and HCO^+ lines observed in the dark clouds are weak, their intensity ratio is proportional to the abundance ratio of these two isotopes, whether the optical depth is small or not; thus relation (1) is always valid in a first approximation. As a check, we have estimated R from radiative transfer calculations in a spherical cloud with a large velocity gradient for $n(H_2)$ between 10^4 and 10^5 cm^{-3}; these estimates are within a factor of 2 of those of Table 1 and are always larger. The same type of model calculations for DR 21(OH) indicate relatively small HCO^+ and DCO^+ optical depths and, again, yield values of R comparable to those of Table 1. We conclude that, taken together, these effects are very unlikely to change the limits of Table 1 by a factor exceeding 4.

Chemical fractionation reactions have been invoked to explain the enhanced abundances of deuterated molecules. The most prominent type of fractionation reaction, introduced by Watson (1974*a*, *b*), consists of isotope exchange reactions of the form:

$$AH^+ + HD \leftrightharpoons AD^+ + H_2 + \Delta E\,. \tag{2}$$

In particular, $H_3^+ + HD \leftrightharpoons H_2D^+ + H_2 + \Delta E$ in cold clouds proceeds from H_3^+ to H_2D^+ because the binding energy of H_2D^+ is slightly larger than that of H_3^+ ($\Delta E/k \sim 180$ K according to Watson 1976).

Reaction (2) has been studied for H_3^+, CH_3^+, HCO^+, H_2CN^+, H_3O^+, and NH_4^+ (Huntress 1977). Its rate constant k_2, measured at 300 K, is equal to 3×10^{-10} cm^3 s^{-1} for H_3^+, 5×10^{-10} cm^3 s^{-1} for CH_3^+, and is less than 10^{-11} cm^3 s^{-1} for the other ions, suggesting that only the first two ions are important for fractionation. Potentially important ions like $C_2H_2^+$ have not been studied and will not be considered here. The rate constant k_2, however, should not exceed the Langevin value, 2×10^{-9} cm^3 s^{-1}, and the upper limits on x_e will not depend significantly on the nature of the ions undergoing fractionation. Here, as in the following, we make the usual assumption that the ion-molecule rate constants measured in the laboratory apply at the low temperatures prevailing in the interstellar clouds.

TABLE 1

Source	HCO^+		DCO^+			H_3^+		CH_3^+	
	T^* (K)	Δv† (km s^{-1})	T^* (K)	Δv† (km s^{-1})	R	x_e (10^{-8})	x(CO) (10^{-6})	x_e (10^{-8})	x(O) (10^{-6})
Taurus cloud....	1.8 (0.20)‡	1.3	0.25 (0.09)‡	1.2	...	...	...	...	...
Orion A.........	8.8 (0.20)	4.3	0.30 (0.15)	1.2	...	...	...	...	...
NGC 2264:									
00............	4.0 (0.17)	4.1	0.60 (0.20)	1.7	>0.09	<4	<25	<6	<80
1.5′ E, 1′ N...	...	...	0.40 (0.15)	1.5					
L134............	0.70 (0.17)	1.3	0.25 (0.06)	1.0	>0.3	<1	<7	<2	<25
L134 N:									
00............	0.60 (0.17)	1.7	0.55 (0.07)	1.2	>0.8	<0.4	<3	<0.7	<9
1′ W..........	...	...	0.40 (0.17)	1.2					
2′ W..........	0.40 (0.17)	1.5	0.25 (0.07)	1.0					
4′ W..........	(0.17)§	...	(0.08)§	...					
1′ E..........	...	...	0.60 (0.20)	1.5					
2′ E..........	(0.17)§	...	(0.07)§	...	>0.6	<0.6	<4	<1	<15
1′ N..........	...	...	0.55 (0.17)	1.2					
2′ N..........	0.35 (0.17)	1.6	0.40 (0.20)	1.5					
1′ S..........	...	...	0.60 (0.20)	1.2					
2′ S..........	0.30 (0.17)	1.6	0.55 (0.17)	1.5					
L63............	0.90 (0.15)	1.6	0.75 (0.13)	1.2	>0.8	<0.5	<3	<0.17	<10
R CrA..........	4.4 (0.20)	2.1	0.30 (0.15)	2.0	...	...	...	...	...
DR 21(OH)......	2.7 (0.20)	4.3	0.25 (0.07)	1.5	>0.06	<6	<40	<10	<150
S140...........	5.0 (0.20)	3.5	0.20 (0.07)	1.5	...	...	...	...	...

Note.—Positions (1950.0) are as follows: Taurus Cloud ($4^h29^m43^s$; 24°16′55″); Orion A ($5^h32^m46^s$; −5°24′21″); NGC 2264 ($6^h38^m25^s$; 9°32′29″); L134 ($15^h51^m00^s$; −4°26′51″); L134 N(00) ($15^h51^m30^s$; −2°43′31″); L63 ($16^h47^m17^s$; −18°00′00″); R CrA ($18^h58^m33^s$; −37°02′ 02″); DR 21(OH) ($20^h37^m14^s$; 42°12′00″); S140 ($22^h17^m41^s$; 63°03′45″). Offsets from these positions are indicated in minutes of arc. In addition to L134 N, 2E and 4W, we have failed to detect DCO^+ in W3 A, L1544, OMC-2, ρ Oph, NGC 6334 N, G84.7–1, and NGC 7538; the rms noise in one channel was typically 0.17 K for these sources.

† Equivalent width

‡ rms noise in one channel.

§ Not detected.

When a single reaction of the form (2) dominates the production of AD^+, the fractional number of these ions produced per second and per hydrogen molecule can be written $N = k_2 x(\mathrm{HD})$, where x(HD) denotes the fractional abundance of HD relative to H_2. In dense clouds, $n(\mathrm{H}) \ll n(\mathrm{H})_2$, thus making x(HD) smaller than or equal to 4×10^{-5}, twice the cosmic abundance of deuterium D/H (York and Rogerson 1976). Therefore, $N \lesssim 4 \times 10^{-5}\, k_2 \lesssim 8$ 10^{-14} cm^3 s^{-1}.

Destruction of the deuterated ion AD^+ results from (*a*) dissociative recombination with electrons; (*b*) reaction with H_2, i.e., reverse of reaction (2); and (*c*) ion-molecule reactions with atoms and trace molecules such as CO, H_2O, and HD; destruction by grain collisions is negligible. The rate constant of dissociative recombinations for heavy polyatomic ions, measured between 200 and 300 K, is always larger than 10^{-7} cm^3 s^{-1}; this rate exhibits at least a $T^{-1/2}$ dependance and should be of the order of or larger than 10^{-6} cm^3 s^{-1} at 10 K. Recent measurements below 100 K indicate that this result applies also for H_3^+ (Auerbach *et al.* 1977). The fractional number of recombinations is therefore $\gtrsim 10^{-6} x_e$ cm^3 s^{-1}. On the other hand, the fractional number of destructions by ion-molecule reactions may be written as $k_2 \exp(-\Delta E/kT)$ for reactions with H_2, and $k_i x_i$ for reactions with the species i.

Equating the destruction and formation rates, we find:

$$R' = \frac{x(\mathrm{AD}^+)}{x(\mathrm{AH}^+)} < \frac{4 \times 10^{-5} k_2}{10^{-6} x_e + k_2 \exp(-\Delta E/kT) + \Sigma k_i x_i}\,. \quad (3)$$

Relation (3) implies: $x_e \lesssim 40\, k_2/R' < 8 \times 10^{-8}/R'$; similar constraints can be derived for T and x_i.

The most straightforworard way to produce HCO^+ follows from the reaction

$$\mathrm{H_3^+ + CO \rightarrow HCO^+} + H_2\,. \quad (4)$$

H_3^+ and CO are usually abundant; and reaction (4), which proceeds rapidly ($k_4 = 1.7\ 10^{-9}$ cm^3 s^{-1}), can be expected to be the main source of HCO^+. Similarly, the reaction

$$\mathrm{H_2D^+ + CO \rightarrow DCO^+} + H \quad (5)$$

is likely to produce most of the DCO^+ at low temperatures, since for $T \leq 100$ K, H_2D^+ is efficiently formed through equation (2). Reaction (5) competes with $\mathrm{H_2D^+ + CO \rightarrow HCO^+ + HD}$ with a branching ratio presumably 2 times smaller for (5). Since the reaction rates of H_2D^+ and H_3^+ with CO are very probably similar, one has $k_5 \approx k_4/3$. By comparison, the reaction $\mathrm{HCO^+ + HD \rightarrow DCO^+ + H_2}$ which has a rate constant of 1.8×10^{-11} cm^3 s^{-1}, here yields only a negligible fraction of the DCO^+.

Apart from this last reaction, the destruction of HCO^+ and DCO^+ proceeds essentially at the same rate. If the CO abundance is about normal, $x(DCO^+)/x(HCO^+) \approx x(H_2D^+)/3\,x(H_3^+)$, where the H_2D^+/H_3^+ ratio is given by the relation (3). Applying this to the DCO^+/HCO^+ ratios found for the three dark clouds of Table 1 yields: $x_e < 10^{-8}$ and $x(CO) < 10^{-5}$, together with: $x(O + O_2 + C) < 10^{-5}$, $x(N_2) < 7\ 10^{-6}$, $x(H_2O) < 1.3\ 10^{-6}$, and $T < 20$ K.

It should be noted that for large enhancement the abundances of H_2D^+, and possibly HD_2^+, become comparable to that of H_3^+, so that formation of HCO^+ from $H_2D^+ + CO$ and formation of DCO^+ from HD_2^+ by a reaction similar to (5) may not be negligible. It can be seen, however, that these reactions will affect the production of DCO^+ relative to HCO^+ by a factor of at most 2.

Two other HCO^+ and DCO^+ formation channels, which may become important for a low CO abundance, are the reactions $CH_3^+ + O \rightarrow HCO^+ + H_2$ and $CH_3^+ + O_2 \rightarrow HCO^+ + H_2O$, and the parallel reactions leading from CH_2D^+ to DCO^+. The discussion of these channels closely follows that of the H_3^+ channel; CH_2D^+ is also formed by deuterium exchange with HD in a reaction similar to (2), with a rate comparable to that of H_2D^+. It follows that, if CH_3^+ is the sole HCO^+ production channel, limits on x_e comparable to those in the H_3^+ channel still exist. It should be noted, however, that unlike H_3^+, CH_3^+ does not react with CO and therefore requires no stringent constraint on the abundance of this species.

We have solved the more complex case where both the CH_3^+ and the H_3^+ channels contribute to the production of HCO^+. In the CH_3^+ analysis we have included the electron recombination reactions leading to CH and CD, since these may also react with oxygen to produce HCO^+ and DCO^+; for the sake of completeness, deuterium exchange between HD and HCO^+ has also been included. Finally, we have assumed that CH_3^+ is produced through the reaction of C with H_3^+ (Herbst and Klemperer 1973; Langer 1976). Under these conditions, we find that DCO^+ is formed essentially through the $H_2D^+ + CO$ channel when $x(C) < 0.02\,x(CO)$, and HCO^+ through the $H_3^+ + CO$ channel when $x(C) \gtrsim x(CO)$. Accordingly, the constraints on CO, O, and the other trace molecules and atoms vary significantly with the C/CO ratio while, as expected, the condition $x_e \gtrsim 10^{-8}$ holds in all cases. The results derived in the two limiting cases, $x(C) \ll 0.02\,x(CO)$ and $x(C) < x(CO)$, are presented in Table 1.

This upper limit on x_e has important consequences on the abundance of metals, on the hydrogen density and on the hynamics of the gas. The ionization of metals in dense clouds results from charge exchange with polyatomic ions, such as H_3^+ and HCO^+, and proceeds at a rate $\sim 10^{-9}\,x(H_3^+ + HCO^+ + \ldots)\,x(M)$ cm^3 s^{-1}; their neutralization results from radiative recombination with electrons, at a rate $4 \times 10^{-11}\,x_e x(M^+)$ cm^3 s^{-1}, and possibly from collisions with grains (rate probably smaller than $10^{-17}\,x(M^+)$ cm^3 s^{-1} at $T_k = 10$ K). Cosmic rays ionization models yield $x(H_3^+ + \ldots) >$ few $\times 10^{-10}$. Equating the rates of ionization and neutralization, we find $x(M^+)/x(M) \gtrsim 0.1$ and, as $x(M^+) < x_e$, $x(M + M^+) \gtrsim 10^{-7}$; therefore, the metals are probably depleted by more than two orders of magnitude.

The rate of production of polyatomic ions is equal to $\zeta(H_2)/n(H_2)$ cm^3 s^{-1}, where $\zeta(H_2)$ denotes the rate of ionization of H_2 by cosmic rays, and the rate of their dissociative recombinations with electrons is $\sim 10^{-6} x_e x(H_3^+ + \ldots)$ cm^3 s^{-1}; in view of the low abundance of metals just derived, charge exchange with metals and subsequent neutralizations can be neglected. Equating ionizations and recombinations yields $n(H_2) > 10^{22}\,\zeta(H_2)$ cm^{-3} or, assuming that most of the cosmic rays with an energy larger than 100 MeV penetrate the cloud, $n(H_2) \gtrsim$ few $\times 10^4$ cm^{-3}. This high value probably means that strong deuterium enhancement occurs only in the very dense core of the clouds.

Finally, the upper limit to x_e implies a very low abundance for the ions and thus affects the coupling of the neutral gas to the magnetic field. The gas can decouple from the magnetic field if the ion diffusion time is short compared to dynamical times. Following Spitzer (1968), the diffusion time in an H_2 gas can be written as $t_D = 3 \times 10^{-39}\,(Ln/B)^2\,x_e$ years, where L is the size of the region (in cm), n its density (in cm^{-3}), and B the magnetic field (in gauss). In the most favorable case for coupling, B can be scaled from its value $B_0 \approx 3 \times 10^{-6}$ gauss in the interstellar medium ($n_0 \sim 0.1$ cm^{-3}) according to the relation $B = B_0(n/n_0)^{1/3}$ (Mouschovias 1976). By using the values derived above, $n \approx 3\ 10^4$ cm^{-3}, $L \approx 0.3\ 10^{18}$ cm, and $x_e \lesssim 10^{-8}$, we find $t_D \lesssim 10^5$ years, whereas the dynamical time for collapse, $t_J = (4\pi G\rho)^{-1/2}$, is $\sim 10^5$ years. Accordingly, the usual assumption of a strong coupling of the gas to the field may not be valid in the central region of the three dark clouds, which possibly indicates that this region is in gravitational collapse.

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REFERENCES

Auerbach, D., Cacak, R., Caudano, R., Gaily, T. D., Keyser, C. J., McGowan, J. W. M., Mitchell, J. B. A., and Wilk, S. F. J. 1977, *J. Phys. B.*, in press.
Goldreich, P., and Kwan, J. 1974, *Ap. J.*, **189**, 441.
Herbst, E., and Klemperer, W. 1973, *Ap. J.*, **185**, 505.
Hollis, J. M., Snyder, L. E., Lovas, F. J., and Buhl, D. 1976, *Ap. J. (Letters)*, **209**, L83.
Huntress, W. T. 1977, *Ap. J. Suppl.*, **33**, 495.
Langer, W. D. 1976, *Ap. J.*, **210**, 328.
Mouschovias, T. Ch. 1976, *Ap. J.*, **207**, 141.
Spitzer, L., Jr. 1968, *Diffuse Matter in Space* (New York: Interscience).
Watson, W. D. 1974*a*, *Ap. J.*, **188**, 35.
———. 1974*b*, *Ap. J.*, **189**, 221.
———. 1976, *Rev. Mod. Phys.*, **48**, 513.
———. 1977, in *CNO Processes in Astrophysics*, ed. J. Audouze (Dordrecht: Reidel).
York, D. G., and Rogerson, J. B., Jr. 1976, *Ap. J.*, **203**, 378.