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OBSERVATIONS OF ANOMALOUS INTENSITIES IN THE LINES OF THE HCO^+ ISOTOPES

WILLIAM D. LANGER
University of Massachusetts, Amherst; and Bell Telephone Laboratories, Crawford Hill Laboratory, Holmdel, New Jersey

ROBERT W. WILSON AND PAUL S. HENRY
Bell Telephone Laboratories, Crawford Hill Laboratory, Holmdel, New Jersey

AND

MICHEL GUÉLIN*
Goddard Institute for Space Studies, New York City
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ABSTRACT

The $J = 1$–0 rotational line of $H^{13}CO^+$ has been detected in the dark clouds L134N and Taurus Molecular Cloud 1 (TMC-1) and found to have, at selected positions, an intensity about twice that of the common isotope. The corresponding $HC^{18}O^+$ observations, however, yield a normal $H^{13}CO^+/HC^{18}O^+$ isotope ratio. We suggest that low-excitation foreground material is absorbing the HCO^+ emission. The presence of this cold material must also affect the lines of other abundant molecules with large dipole moments, such as HCN, H_2CO, and CS; these lines should be used cautiously as probes of the high-density dark clouds, and the less abundant isotopic species should be observed to check for opacity effects.

Subject headings: interstellar: abundances — interstellar: molecules

I. INTRODUCTION

The rotational lines of molecules with large excitation rates, such as HCO^+, H_2CO, and CS, have been used to study the physical conditions in the high-density regions of interstellar clouds (Martin and Barrett 1975; Evans and Kutner 1976; Guélin *et al.* 1977). In order to extend these studies, we have mapped the $J = 1$–0 rotational lines of five isotopes of the formyl ion in the cool dark clouds L134N and TMC-1 (Taurus Molecular Cloud 1; often referenced in the literature as Heiles's Cloud 2). At a few selected positions in these clouds we have also observed the $J = 1$–0 lines of N_2H^+, N_2D^+, and HCN.

Our observations have revealed the presence of very strong $H^{13}CO^+$ and DCO^+ emission in each cloud. Whereas the presence of the strong DCO^+ emission in L134N could be inferred from observations of the $J = 2$–1 DCO^+ lines (Guélin *et al.* 1977), our detection of $H^{13}CO^+$ lines which exceed the lines of the normal isotope in intensity was unexpected. Prior observations of $H^{13}CO^+$ (Snyder *et al.* 1976; Watson, Snyder, and Hollis 1978) had not revealed an intensity exceeding one-tenth or two-tenths that of HCO^+. The strength of the DCO^+ lines was explained in terms of deuterium fractionation (Guélin *et al.* 1977). The interpretation of the strength of the $H^{13}CO^+$ emission and its application to the understanding of the physical conditions in clouds are the subjects of this *Letter*.

II. OBSERVATIONS

These observations were carried out from 1977 November through 1978 April with the Bell Laboratories 7 m antenna in Holmdel, New Jersey (Chu *et al.* 1978). The telescope's angular resolution is about 2′ at the frequency of the $J = 1$–0 rotational line of HCO^+ (~89 GHz). The frequency resolution of 62.5 kHz (or 0.21 km s^{-1} for HCO^+) was achieved by using a spectrum expander (Henry 1977) with a spectral coverage of 6.5 MHz. The lines were observed by frequency-switching so that both responses were within the expanded spectrum. A cooled mixer receiver (Linke, Schneider, and Cho 1978) with a SSB noise temperature of 300 to 400 K was used with a Fabry-Perot filter giving 15 dB image rejection. Calibrations were performed by chopping between a room-temperature absorber and an absorber cooled by liquid nitrogen (Goldsmith 1977). The observations were corrected for atmospheric absorption by using the sky temperature measured by chopping between the antenna and the cold absorber. The critical measurements of HCO^+ and $H^{13}CO^+$ shown in Figures 1 and 2 were made on the same evening with a minimum time between measurements; the calibration at both frequencies was checked by measuring the antenna temperature of Jupiter and found to be the same.

III. RESULTS

The most striking example of strong $H^{13}CO^+$ emission is presented in Figure 1, which displays the line profiles of the HCO^+ isotopes in TMC-1 at the position of the ^{13}C maximum. At the velocity of its peak (~5.6 km s^{-1}), the $H^{13}CO^+$ line is 1.8 times stronger than that of HCO^+, which corresponds to a ratio of $^{13}C/^{12}C$ some 160 times larger than the terrestrial abundance ratio. In contrast, the observed $H^{13}CO^+/HC^{18}O^+$ peak and integrated line intensity ratios (about 6) are approximately equal to the terrestrial abundance ratio. Similar

* On leave from Département de Radioastronomie, Observatoire de Paris.

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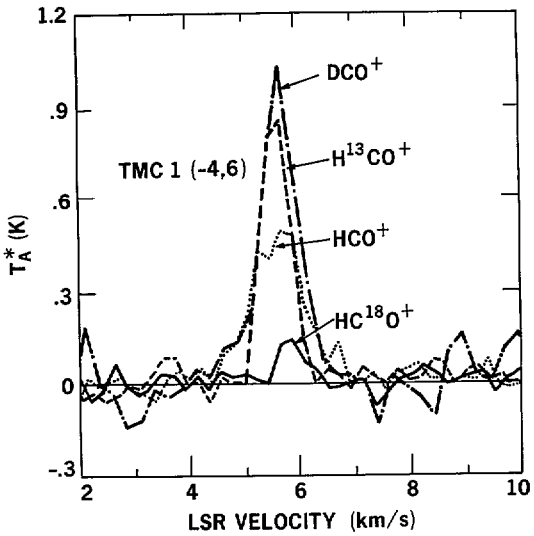

FIG. 1.—Spectra are displayed for the 1–0 line of the following HCO^+ isotopes in the Taurus Molecular Cloud (TMC-1): HCO^+ (89, 188.545 GHz); $H^{13}CO^+$ (86,754.34 GHz); $HC^{18}O^+$ (85,162.157 GHz); and DCO^+ (72,039.35 GHz). The reference position (0, 0) for this cloud is $\alpha(1950) = 4^h38^m38^s$, $\delta(1950) = 25°35'45''$, and the velocity in the local standard of rest $v_{LSR} = 5.9$ km s^{-1}. The spectra presented here are at the position of the $H^{13}CO^+$ maximum, (−4, 6), measured with respect to the reference position in minutes of arc.

values are derived near the center of L134N (see Figs. 2 and 3). We also searched for $D^{13}CO^+$ (70,733.2 GHz; Woods *et al.* 1977) and found only an upper bound in TMC-1 and L134N, T_A^* ($D^{13}CO^+$) < 0.08 K (2 σ); both the peak and integrated intensity ratios require an isotope ratio, $^{12}C/^{13}C > 15$.

In TMC-1 the HCO^+ line (Fig. 1) has a fairly symmetrical shape, and is in good velocity agreement with the lines of $H^{13}CO^+$, $HC^{18}O^+$, and DCO^+. In contrast the HCO^+ line at the center of L134N (Fig. 2) is broad and very asymmetrical, and peaks at a much higher velocity than the $H^{13}CO^+$, $HC^{18}O^+$, and DCO^+ lines. The velocity of these latter isotopes (2.4 km s^{-1}) is consistent with that of ^{13}CO (unpublished data), 2.6 km s^{-1}. A similar shift is also visible at a position (−2′, 4′) away from the central position (Fig. 3).

Our observations of HCN at the center of L134N indicate that the shape and velocity of these lines match almost exactly those of HCO^+ (i.e., they are asymmetrical and peak at 3.5 km s^{-1}). In TMC-1, however, the three hyperfine lines are symmetrical and their intensities are nearly equal, T_A^*(HCN) ~ 0.8 K; this represents a significant departure from the ratios of their relative transition strengths.

We have observed DCO^+ in order to derive fractional electron abundances in these clouds (see Guélin *et al.* 1977). The DCO^+ lines shown in Figures 1–3 have antenna temperatures greater than those of HCO^+ and, what is most important, peak at the same v_{LSR} as do the $H^{13}CO^+$ lines.

N_2H^+ and N_2D^+ observations can also be used to derive electron abundances and, as noted by Snyder *et al.* (1977), the N_2H^+ is a potentially useful probe because theoretically its line opacity can be checked. Unfortunately, the N_2D^+ lines are very weak and have so far been detected in only one source, L134N (Snyder *et al.* 1977). We have resolved the 1–0 N_2D^+ lines in this source and have observed it in TMC-1, $T_A^*(N_2D^+) \approx 0.1$ K.

IV. DISCUSSION

Two processes can contribute to the enhancement of the ^{13}C to ^{12}C isotopic intensity ratios in HCO^+, namely, ^{13}C fractionation and HCO^+ self-absorption. Exchange

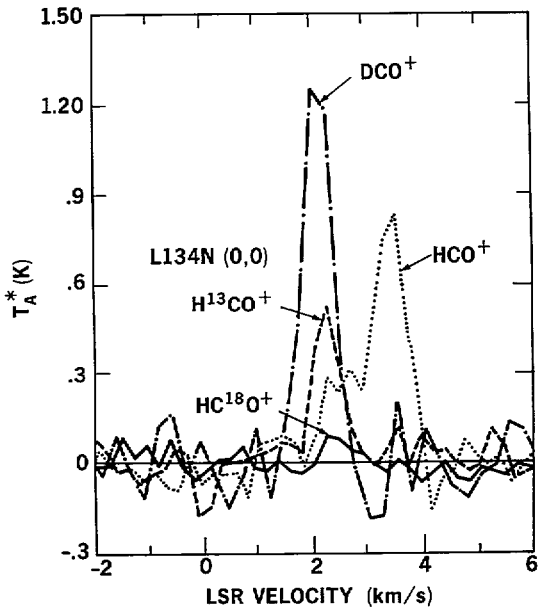

FIG. 2.—Spectra for the HCO^+ isotopes at the central position (0, 0) in L134N. This position has the (1950) coordinates $\alpha = 15^h51^m30^s$, $\delta = -2°43'31''$, and $v_{LSR} = 2.5$ km s^{-1}. The peak in T_A^* for HCO^+ occurs at $v_{LSR} = 3.5$ km s^{-1}, while those for both $H^{13}CO^+$ and $HC^{18}O^+$ are at 2.4 km s^{-1}, and the DCO^+ emission peaks at 2.0 km s^{-1}.

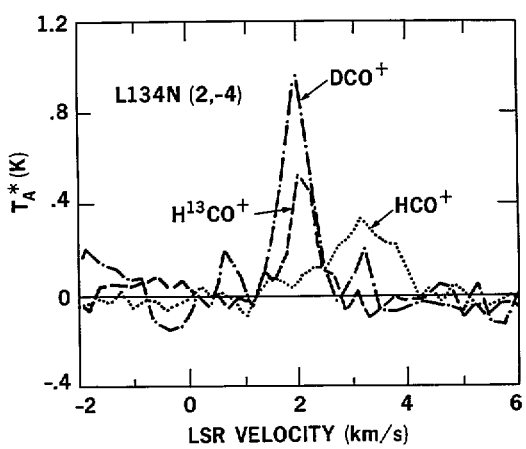

FIG. 3.—Spectra for HCO^+, $H^{13}CO^+$, and DCO^+ at the position (2′, −4′) in L134N (see Fig. 2 for the reference position). Hardly any HCO^+ emission is evident at $v_{LSR} = 2.0$ km s^{-1}, where both $H^{13}CO^+$ and DCO^+ peak.

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of ^{13}C between C^+ and CO has been discussed by Watson, Anicich, and Huntress (1976) and Langer (1977). This reaction has been shown to lead to ^{13}C enhancement for carbon monoxide (and for those molecules formed primarily from CO) in the dark molecular clouds, but by a factor hardly exceeding 3 or 4. Another ^{13}C exchange reaction which could conceivably enhance the ^{13}C abundance in HCO^+ is the protonation reaction

$$H^{12}CO^+ + {}^{13}CO \rightarrow H^{13}CO^+ + {}^{12}CO\,; \qquad (1)$$

whether this reaction is exothermic and proceeds rapidly is unknown. Evidence that ^{13}C fractionation is not large is provided by the nearly terrestrial value of the $H^{13}CO^+/HC^{18}O^+$ ratio and from the limit $DCO^+/D^{13}CO^+ > 15$. Furthermore, it can be shown from an analysis similar to that for deuterium fractionation (Guélin *et al.* 1977) that reaction (1) would explain the observed intensity ratios only under extreme (and unlikely) physical conditions. We conclude that the relative strength of the $H^{13}CO^+$ line compared with that of the HCO^+ line results instead from the high opacity in the latter line.

In view of the apparent weakness of the HCO^+ ($T_A^* \ll T_k$, where $T_k \sim 10$ K is indicated by the excitation temperature of the $J = 1$–0 CO lines in these sources), saturation should have only a small effect on the $H^{13}CO^+/HCO^+$ abundance ratio. The near-normal $H^{13}CO^+/HC^{18}O^+$ ratios suggest that lines with $T_A^* \lesssim 0.5$ K underestimate the column density by at most a factor of 2 (this limit on the saturation is also consistent with theoretical estimates of peak antenna temperatures based on an LTE model of radiative transfer). We conclude that lines of HCO^+ (and its isotopes) which have $T_A^* < 1$ K should not be strongly saturated in these clouds. Obviously, saturation in a cloud with a uniform HCO^+ excitation temperature cannot account for $H^{13}CO^+$ lines stronger than those of the normal isotope.

It is unrealistic, however, to assume a uniform excitation temperature for any molecular species, since interstellar clouds have gradients in density, kinetic temperature, and fractional abundances; furthermore, a foreground cloud with a different excitation temperature may exist along the line of sight. We suggest that the presence of such gradients or foreground clouds leads to self-absorption, which can explain the relative intensities of the HCO^+, $H^{13}CO^+$, and $HC^{18}O^+$ lines (see the related calculations for self-absorption in CO by Kwan 1978). To simplify our discussion of this problem, we consider a two-component model of these sources having foreground material with a relatively low excitation temperature absorbing the HCO^+ radiation from a high-excitation region. In this model the emission arises primarily from dense gas where the collision rate is sufficient to excite not only HCO^+ but also its rarer isotopes; the DCO^+ emission suggests a high density for this gas, since deuterium enhancement is believed to occur in dense regions where the electron abundance is low. The absorption occurs in the low-density foreground material which is either a foreground cloud or an envelope surrounding a high-density core.

For a hydrogen density, $n(H_2)$, of 10^3 cm^{-3} and a kinetic temperature of 10 K, the collisional de-excitation rate for the $J = 1$ level of HCO^+ is about 200 times smaller than the rate of spontaneous emission. The HCO^+ excitation temperature, T_{ex}, is then essentially determined by radiative processes, and should be close to the 2.8 K background in the absence of any other strong source of radiation. In denser regions, $n(H_2) \gtrsim$ a few times 10^4 cm^{-3}, the collisional excitation rate is large enough to raise T_{ex} to a substantial fraction of T_k. A low-density cloud or envelope with $n(H_2) \sim 10^3$ cm^{-3} is therefore likely to have an HCO^+ excitation temperature much lower than that of the high-density inner region where $n(H_2) > 10^4$ cm^{-3}. Even in the case where the HCO^+ column density in the low-excitation foreground region is relatively low, the HCO^+ line may be optically thick because this molecule has a large dipole moment ($\sim$3 debye). An optical depth of 1, for example, can be realized in the foreground cloud with $A_v \sim 1$ mag and an HCO^+ fractional abundance as low as 4×10^{-10}. The low excitation temperature and relatively large optical depth in the HCO^+ line will cause absorption in the HCO^+ line. Because of the much lower $H^{13}CO^+$ and $HC^{18}O^+$ abundances, the lines of these molecules are likely to have an opacity small enough so that absorption is not significant. This model explains the relative weakness of the normal HCO^+ isotopic species as well as the nearly terrestrial $H^{13}CO^+/HC^{18}O^+$ intensity ratios. For similar reasons, absorption by low-excitation foreground material can be important for other abundant molecules which have large dipole moments, such as HCN, H_2CO, and NH_3.

In TMC-1 the results presented in § III and Figure 1 suggest that the foreground absorbing material could be an envelope, since it has about the same velocity as the dense central region and at least a comparable velocity dispersion; Sume, Downes, and Wilson (1975), however, found evidence from H_2CO observations of two components in this source with velocities of 5.3 and 6.1 km s^{-1}. Direct evidence for two components occurs in L134N from the velocity structure of the lines presented in Figures 2 and 3 as well as the HCN observations discussed in § III. Furthermore, the observations at the position (2′,− 4′) imply that both the dense core and the absorbing foreground material are extended.

Molecules with large dipole moments have been used to interpret physical conditions in dense clouds. For example, hydrogen densities have been inferred from the intensity of the millimeter lines of H_2CO (Evans *et al.* 1975; Lucas, Encrenaz, and Falgarone 1976) and CS (Martin and Barrett 1975); ionization rates from those of HCO^+, HCN, and HNC (Wootten *et al.* 1978); and electron and CO abundances by using DCO^+/HCO^+ (Guélin *et al.* 1977) and N_2D^+/N_2H^+ (Snyder *et al.* 1977). However, the results presented here indicate that these lines may be absorbed by foreground material and should be used cautiously as probes of the high-density regions. This may be relevant, for example, to the discrepancies noted by Lucas *et al.* between the intensities of the 6 cm and 2 mm lines of H_2CO. Evans and Kutner (1976)

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cautioned against the use of these lines to derive densities in L134N, since the velocities of the 6 cm and 2 mm lines did not agree. Evidence that absorption by low-excitation foreground material also occurs for the HCN lines comes from spectra of its hyperfine components (see § III). At the center of L134N the shape and velocity of these lines match almost exactly those of HCO^+. In TMC-1 the intensities of the three hyperfine lines are too weak to be strongly saturated, and we suggest instead that their nearly equal intensities are another effect of absorption by foreground material. In a two-component model it would also be possible to have a reversal of the intensities of the hyperfine lines. The possibilities of absorption by foreground material suggest the importance of using low-abundance isotopes to evaluate physical conditions in the clouds, as is illustrated below.

Guélin *et al.* (1977) derived the electron and CO fractional abundances at the center of L134N from the intensities of the HCO^+ and DCO^+ lines, and found $n(e)/n(H_2) \leq 10^{-8}$ and $n(CO)/n(H_2) \leq 10^{-6}$; on the basis of radiative-transfer calculations in a homogeneous cloud, they quote an uncertainty of at most a factor of 4. The strong self-absorption in the line of Figure 2, which arises from the presence of two distinct components in this source, suggests that the above fractional abundance limits may be underestimated by a large factor. More conservative limits can be derived by using the $H^{13}CO^+$ instead of the HCO^+ line and assuming that the $HCO^+/H^{13}CO^+$ ratio is known (here we assume a ratio of 40). The data in Figure 2 now yield $n(e)/n(H_2) < 5 \times 10^{-8}$ and $n(CO)/n(H_2) < 3 \times 10^{-5}$ at the velocity of the $H^{13}CO^+$ peak (2.4 km s^{-1}); at $v_{LSR} = 1.9$ km s^{-1} these values are 3×10^{-8} and 2×10^{-5}, respectively. A similar analysis for TMC-1 (see Fig. 1) yields $n(e)/n(H_2) < 1 \times 10^{-7}$. A limit of 4×10^{-8} has also been derived in another dark cloud, L134, from $H^{13}CO^+$ by Watson, Snyder, and Hollis (1978). Our N_2D^+/N_2H^+ ratios indicate that $n(e)/n(H_2) \lesssim 2 \times 10^{-8}$ and 3×10^{-8} in L134N (similar to Snyder *et al.* 1977) and TMC-1, respectively. These values are lower by a factor of 4 than those derived by using $H^{13}CO^+$ and are perhaps a result of absorption in N_2H^+. The new limits on $n(e)/n(H_2)$, although higher than derived by Guélin *et al.* (1977), still imply a low value in these clouds.

The discussion presented here illustrates the difficulty of interpreting spectra of molecules with large dipole moments, and suggests the importance of using low-abundance isotopic or chemically localized species to interpret the physical properties of dense clouds. We suggest that the interpretation of the radiation arising in the dense core is complicated by the presence of low-excitation gas, either surrounding or in front of the dense core, which absorbs and scatters the radiation into other portions of the foreground material. The spectra observed along the line of sight to the high-excitation core consist of a transmitted plus a scattered component. Even the interpretation of the physical conditions of the surrounding gas (i.e., not along the line of sight to the dense region) made by mapping only the most abundant isotope may be misleading, since even near the edge of the foreground region the line emission reflects not only the local conditions but also those in the core.

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MICHEL GUÉLIN: Radioastronomie, Observatoire de Paris, 92190 Meudon, France

PAUL S. HENRY and ROBERT W. WILSON: Bell Telephone Laboratories, Crawford Hill Laboratory, Holmdel, NJ 07733

WILLIAM D. LANGER: Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003

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