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DEUTERIUM IN THE GALAXY

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ABSTRACT

A survey of millimeter-wave line emission from the deuterated and carbon-13 isotopes of interstellar hydrocyanic acid (DCN and $H^{13}CN$) has been carried out. The results indicate that the [DCN]/[HCN] abundance ratio is about 100 times the "local" (i.e., within ~200 pc of the Sun) [D]/[H] ratio over a large portion of the Galaxy, with relatively little source-to-source variation. The [DCN]/[H^{13}CN] abundance ratio in Sgr B appears to be markedly lower than in the other sources. We associate this apparent deuterium deficiency with a greater amount of stellar processing of the material near the galactic center, implying that such processing leads to a net destruction of deuterium. This result seems to eliminate stellar activity as a principal source of observed deuterium.

Subject headings: abundances — deuterium — galaxies: Milky Way — galaxies: nuclei — molecules: interstellar

I. INTRODUCTION

The discovery of interstellar deuterium in deuterated hydrocyanic acid (DCN) (Jefferts, Penzias, and Wilson 1973) was greatly facilitated by the relatively high DCN/HCN abundance ratio, $\sim 3 \times 10^{-3}$, found in the source observed. In this source, Ori A, DCN was found to be some 100 times more abundant relative to HCN than the estimated proto-solar [D]/[H] value of 3×10^{-5} (Geiss and Reeves 1972). This enhanced abundance of DCN has been attributed to chemical fractionation, with several possible mechanisms suggested (Solomon and Woolf 1973; Watson 1973, 1974). Subsequent observations, made with the *Copernicus* satellite, of the deuterium and hydrogen Lyman lines in the lines of sight to five stars yielded a value [D]/[H] of $\sim 1.8 \times 10^{-5}$ which is thought to be representative of the region within 200 pc of the Sun (York and Rogerson 1976). In order to determine the interstellar [D]/[H] ratio at distances greater than a few hundred parsecs, other observing techniques must be used. The most promising of these techniques seems to be a DCN survey in strong molecular sources, especially if the effects of fractionation can be correctly evaluated. The results of such a survey are described herein, along with a discussion of the effects of chemical fractionation.

The chief goal of the work described herein is the comparison of the deuterium abundance in the outer portion of the Galaxy with that in the inner portion. The result of such a comparison can be used to determine whether deuterium is of Galactic or cosmological origin. If the observed deuterium is primordial, then strong constraints are put on the cosmological parameters by the simple big-bang nucleogenic scenario. (See, for example, Gott *et al.* 1974.) If deuterium is primarily produced by stars, then it should have a higher abundance in the metal-rich portions of the Galaxy (Ostriker and Tinsley 1975). Deuterium produced in the initial big bang will have a greater relative abundance in metal-poor regions since it is destroyed by astration. Because the central portion of the Galaxy has the highest metal abundance, the problem reduces to a determination of the sign of the radial gradient of the Galactic distribution of the deuterium abundance. Deuterium produced by stars should be relatively more abundant toward the Galactic center, while primordial deuterium should have the opposite distribution.

II. OBSERVATIONS

We have measured line emission from the 144,828 MHz $J = 2 \rightarrow J = 1$ rotational transition of $^2H^{12}C^{14}N$ (DCN) and the 86,340 MHz $J = 1 \rightarrow J = 0$ transition of $H^{13}C^{14}N$ ($H^{13}CN$) in the dense molecular clouds Sgr B2, M17, W51, DR 21, DR 21 OH, Ori A, and NGC 2264. In all cases measurements were made in the direction of strongest molecular line emission in each source. In addition, a four-point north-south strip map about 1 pc in extent was made in the Ori A molecular cloud. All of the DCN observations were made with the 5 m diameter radio telescope of the University of Texas Millimeter Wave Observatory[1] which has a beamwidth of ~1′.5 at the wavelength of observation (2.1 mm). The $H^{13}CN$ observations were made with the 11 m diameter NRAO radio telescope at Kitt Peak[2] whose beamwidth at 86 GHz is 1′.3, comparable to that of the smaller University of Texas

[1] The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory of the University of Texas at Austin, with support from the National Aeronautics and Space Administration, the National Science Foundation, and McDonald Observatory.

[2] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

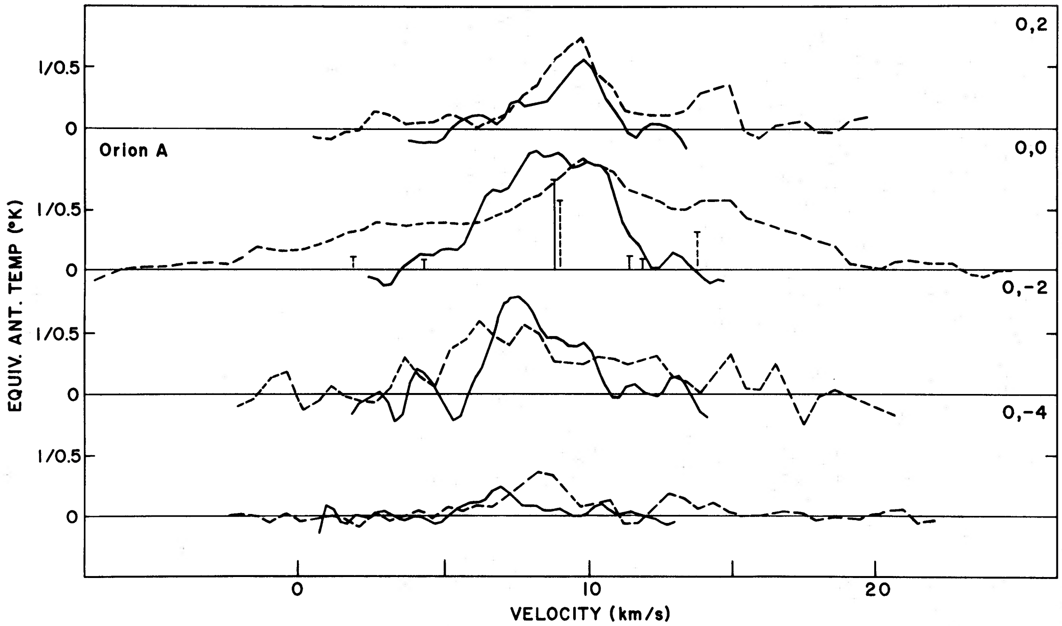

FIG. 1.—DCN and $H^{13}CN$ in Orion A. The plotted spectra were taken at four locations in the source. The numbers in the upper right-hand corner of each figure denote R.A. and decl. displacements from the central position in minutes of arc. The ordinates are antenna temperature corrected for antenna efficiency and atmospheric absorption, with the larger number referring to the $H^{13}CN$ spectra (*dashed line*). Hyperfine structure for the two species are plotted for the central feature.

telescope used at the higher DCN frequency. Details of the observing procedures have been reported earlier (Wannier *et al.* 1976).

The sources for our DCN survey were selected from those sources found to have appreciable line intensities in a preliminary survey of $H^{13}CN$ emission from the well known molecular line sources. This selection was made somewhat arbitrarily, in order to allow a sufficient amount of observing time per source, consistent with efficient use of the total time available. Thus the strong source NGC 6334 was not included because it conflicted with the Sgr B2 and M17 observations, while the much weaker source NGC 2264 was included because its right ascension makes it observable after all other suitable Galactic sources have set.

Our observed spectra are plotted in Figures 1 and 2 and summarized in Table 1. Both the $H^{13}CN$ and DCN transitions are split into hyperfine multiplets. The frequencies and relative intensities of the components are listed in Table 2. The $F = 1 \rightarrow F = 1$ component of the DCN multiplet lies 2.2 MHz above the dominant component, the unresolved blend of the $F = 2 \rightarrow F = 1$ and $F = 3 \rightarrow F = 2$ transitions. When the frequency switching was set up to produce observable features during both halves of the switching cycle in the 10 MHz wide (40 × 0.25 MHz) spectrometer, the $F = 1 \rightarrow F = 1$ component was located at the low-velocity edge of the resulting spectrum. Although this problem was taken into account when the baselines were drawn for data reduction, a small ($\leqslant 5\%$) systematic underestimate of the DCN integrated intensities in the Ori A, NGC 2264, DR 21, and M17 results. It has been included in our estimate of the overall errors.

TABLE 1

LINE FREQUENCIES AND RELATIVE INTENSITIES*

Species	Transition	Frequency (MHz)	Relative Intensity
$H^{13}CN$.......	$J = 1 \rightarrow J = 0$, $F = 1 \rightarrow F = 1$	88,630.42	0.333
	$F = 2 \rightarrow F = 1$	88,631.85	0.555
	$F = 0 \rightarrow F = 1$	88,633.94	0.111
DCN.........	$J = 2 \rightarrow J = 1$, $F = 2 \rightarrow F = 2$	144,826.57	0.083
	$F = 1 \rightarrow F = 0$	144,826.82	0.111
	$F = 2 \rightarrow F = 1$	144,828.00	0.25
	$F = 3 \rightarrow F = 2$	144,828.11	0.466
	$F = 1 \rightarrow F = 1$	144,830.34	0.083

* Maki 1974.

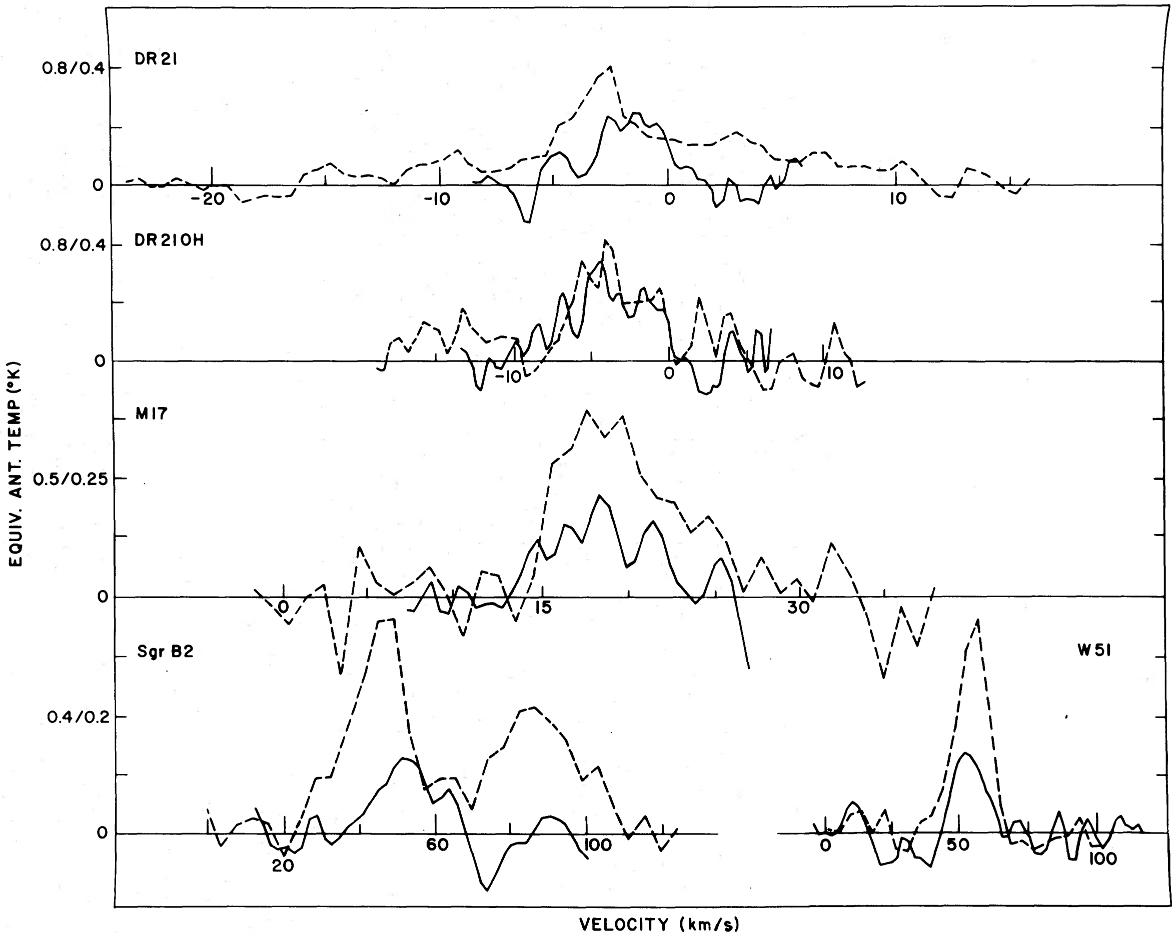

FIG. 2.—DCN and $H^{13}CN$ in various sources. The ordinates are antenna temperature corrected for antenna efficiency and atmospheric absorption, with the larger numbers referring to the $H^{13}CN$ spectra (*dashed lines*). The difference in the shapes of the two species in Sgr B is due to saturation of the $H^{13}CN$ lines, as discussed in the text.

III. DISCUSSION

The isotopic species and transitions, $J = 2 \rightarrow J = 1$ for DCN, and $J = 1 \rightarrow J = 0$ for HCN, were selected to optimize the quality of our results given the observational constraints discussed below. Since the spectra of the most abundant $H^{12}C^{14}N$ (HCN) species are saturated (Wannier *et al.* 1974; Gottlieb *et al.* 1975), their direct use for abundance determinations is unacceptable. Instead, comparisons were made with the rarer $H^{13}CN$ species. Although the 172,678 MHz $J = 2 \rightarrow J = 1$ line of the $H^{13}CN$ is more intense than the $J = 1 \rightarrow J = 0$ line (Wilson *et al.* 1972), observations at frequencies above 160 GHz are made very difficult by the broad atmospheric water vapor absorption feature centered at 183 GHz. Finally, while both the 145 GHz $J = 2 \rightarrow J = 1$ and 72 GHz $J = 1 \rightarrow J = 0$ DCN lines lie in regions of reasonable atmospheric transparency, the greater intensity of the former and the proximity of a formaldehyde line to the latter outweigh the difficulty associated with making comparisons between different transitions in the two isotopic species.

In order to relate the relative intensities of the lines observed to relative column densities an estimate of rotational excitation must be made. In the strong excitation limit the rotation levels of each isotopic species are populated according to their statistical weights, and the integrated line intensities are given by the relations (1) and (2):

$$\int \Delta T_A(\mathrm{DCN}\ 2 \rightarrow 1)dv = \frac{5c^3 A_{21} N_0(\mathrm{DCN})}{8\pi(\nu_{21})^3}\left[1 - \exp\left(-\frac{h\nu_{21}}{kT_{21}}\right)\right]T_{21}\,, \tag{1}$$

where ΔT_A is the antenna temperature corrected for antenna efficiency and atmospheric absorption, ν_{21} is the

TABLE 2

SUMMARY OF OBSERVATIONS

Source (*a*)	α(1950) (*b*)	δ(1950) (*c*)	ΔT_A ($H^{13}CN$) (*d*)	ΔT_A (DCN) (*e*)	$\int \Delta T_A dv / \int \Delta T_A dv$ (*f*)	$N(DCN)/N(H^{13}CN)$ (*g*)	T/T_{Ori} (*h*)	R_{gal} (kpc) (*i*)
W3	2:21:55	61:52:00	0.3 ± 0.3	...	...	...	0.38	12.2
W3 (OH)	2:23:17	61:39:00	0.5 ± 0.2	...	...	...	0.37	12.2
Ori A	5:32:45	−5:24:30	2.0 ± 0.1	0.9 ± 0.1	0.26 ± 0.05	0.182 ± 0.036	1.00	10.9
0, 2′	...	...	1.4 ± 0.2	0.5 ± 0.15	0.22 ± 0.05	0.154 ± 0.036		
0, −2′	...	...	1.0 ± 0.3	0.7 ± 0.2	0.30 ± 0.06	0.210 ± 0.040		
0, −4′	...	...	0.6 ± 0.2	0.2 ± 0.1	0.21 ± 0.06	0.147 ± 0.042		
NGC 2264	6:38:25	9:32:00	0.45 ± 0.15	0.1 ± 0.1	...	...	0.45	11.1
NGC 6634	17:17:29	−35:44:00	1.3 ± 0.2				0.49	9.3
Sgr A–IR	17:42:30	−28:59:15	0.25 ± 0.1				0.31	
Sgr A–CO	17:42:42	−28:59:00	0.7 ± 0.2				0.37	
Sgr B2	17:44:11	−29:22:30	0.8 ± 0.1	0.12 ± 0.03	0.086 ± 0.02	0.018 ± 0.012	0.33	0.1
0, 1′	...	...	0.5 ± 0.2					
0, −1′	...	...	0.4 ± 0.2					
1′, 0	...	...	0.6 ± 0.2					
1′, 0	...	...	0.5 ± 0.2					
W31	18: 5:58	−20:06:05	0.35 ± 0.2				0.26	8.3
M17	18:17:26	−16:14:54	0.9 ± 0.1	0.15 ± 0.05	0.18 ± 0.06	0.126 ± 0.42	0.65	8.0
W51	19:21:27	13:24:30	0.8 ± 0.1	0.12 ± 0.03	0.18 ± 0.04	0.126 ± 0.28	0.50	7.6
DR 21	20:37:13	42:08:51	0.8 ± 0.15	0.20 ± 0.05	0.12 ± 0.03	0.084 ± 0.022	0.41	9.9
DR 21 (OH)	20:37:13	42:11:51	0.7 ± 0.2	0.25 ± 0.05	0.30 ± 0.10	0.21 ± 0.070	0.45	9.9
NGC 7538	23:11:37	61:12:00	0.6 ± 0.1	...	...	...	0.40	12.7

NOTES TO TABLE 2.—ΔT_A is the peak antenna temperature corrected for antenna efficiency and atmospheric absorption. In Sgr B2 the peak $H^{13}CN$ antenna temperature (*d*) refers to the peak near 45 km s^{-1}. The ratios of column density (*g*) were obtained from the corresponding ratios of integrated line intensity (*f*) in each source by means of relation (6), except for Sgr B2 where a correction for line saturation was made (see text). The error limits listed are estimated maximum errors and are dominated by baseline uncertainties. Column (*h*) is the kinetic temperature relative to Ori A as determined from the corresponding CO brightness temperatures (Penzias *et al.* 1971; Liszt 1973; Wannier *et al.* 1976). Column (*i*) lists the distance (in kpc) of each source from the galactic center.

$J = 2 \rightarrow J = 1$ rotational transition frequency, A_{21} is the spontaneous emission rate, and N_0(DCN) is the DCN column density in the $J = 0$ state. Similarly,

$$\int \Delta T_A(\mathrm{H^{13}CN}\ 1 \rightarrow 0)dv = \frac{3c^3 A_{10} N_0(\mathrm{H^{13}CN})}{8\pi(\nu_{10})^3}\left[1 - \exp\left(-\frac{h\nu_{10}}{kT_{10}}\right)\right]T_{10}\,. \tag{2}$$

In this limit of strong excitation we may expand the exponentials and combine the two expressions to yield

$$\frac{N_0(\mathrm{DCN})}{N_0(\mathrm{H^{13}CO})} = \frac{B(\mathrm{H^{13}CN})}{4B(\mathrm{DCN})}\frac{\int \Delta T_A(\mathrm{DCN}\ 2 \rightarrow 1)dv}{\int \Delta T_A(\mathrm{H^{13}CN}\ 1 \rightarrow 0)dv}\,, \tag{3}$$

where the B's are the respective rotation constants of the two species. Since the fraction of the total population located in the ground state is about inversely proportional to the rotation constant (see, for example, Penzias 1975, p. 391), we have the final result:

$$\frac{N(\mathrm{DCN})}{N(\mathrm{HCN})} = \frac{B^2(\mathrm{H^{13}CN})}{4B^2(\mathrm{DCN})}\frac{\int \Delta T_A(\mathrm{DCN}\ 2 \rightarrow 1)dv}{\int \Delta T_A(\mathrm{H^{13}CN}\ 1 \rightarrow 0)dv} = 0.35\frac{\int \Delta T_A(\mathrm{DCN}\ 2 \rightarrow 1)dv}{\int \Delta T_A(\mathrm{H^{13}CN}\ 1 \rightarrow 0)dv} \quad \text{(strong excitation)}\,. \tag{4}$$

Because of the low intensities of the observed lines we need consider only the low optical depth case in the strong excitation limit. We have taken the excitation temperature in the two species to be equal in the above relation since modification of the excitation by radiation trapping effects does not occur at low optical depths.

In the weak excitation limit, the collisional excitation rate is much less than the radiative decay rate. Thus every collisional excitation results in the emission of a photon. However, the $J = 1$ state will be populated at about half of its statistical weight by the 3 K microwave background radiation, so we must also consider collisional deexcitation from the $J = 1$ state. We have

$$T_A(J = 1 \rightarrow J = 0) \propto \left[N_0 \sum_{j=1}^{\infty} \sigma_{0j} - N_1\sigma_{10}\right](\nu_{10})^{-2}$$

and

$$T_A(J = 2 \rightarrow J = 1) \propto \left[N_0 \sum_{j=2}^{\infty} \sigma_{0j} + N_1 \sum_{j=2}^{\infty} \sigma_{1j}\right](\nu_{21})^{-2} ,$$

where the σ's are the cross sections for collision with the ambient neutral gas which provides the excitation. A numerical calculation, employing cross sections calculated by Green and Thaddeus (1974), yields (Linke *et al.* 1977)

$$\frac{N_0(\mathrm{DCN})}{N_0(\mathrm{H^{13}CN})} \lesssim 2.5 \frac{T_A(\mathrm{DCN}\ 2 \rightarrow 1)}{T_A(\mathrm{HCN}\ 1 \rightarrow 0)} \quad \text{(weak excitation)} \tag{5}$$

in the weak excitation limit.

The only source in which all the HCN isotope line intensities have been measured in both the $J = 1 \rightarrow J = 0$ and $J = 2 \rightarrow J = 1$ transitions is Ori A (Wilson *et al.* 1972, 1973). In addition, the $J = 3 \rightarrow J = 2$ line of DCN has also been measured in this source (Phillips, Jefferts, and Wannier 1974). These data indicate a moderately strong rotational excitation corresponding to a line intensity relation intermediate between equations (4) and (5):

$$\frac{N(\mathrm{DCN})}{N(\mathrm{H^{13}CN})} \approx 0.7 \frac{T_A(\mathrm{DCN}\ 2 \rightarrow 1)}{T_A(\mathrm{HCN}\ 1 \rightarrow 0)} . \tag{6}$$

Although this relation was derived from only Ori A data, it should be appropriate to many of the other sources studied as well. Liszt and Linke (1975) studied the excitation in four of the sources in our survey, including Ori A but not Sgr B, by means of CS line measurements and found them to be similar. In the comparison made below, the assumption of an excitation rate for Sgr B corresponding to that in Ori A could lead to an underestimate of the DCN of as much as a factor of 3, if the excitation rate in Sgr B were very low. The existence of many highly excitated lines in Sgr B assures us that a strong excitation rate exists here and that use of relation (6) will not lead to an underestimate of the DCN in this source. (The OCS lines in this source, for example, have been observed up through the $J = 12 \rightarrow J = 11$ transition [Solomon *et al.* 1973]. The intensity of the lines is found to increase with J until about the $J = 8 \rightarrow J = 7$ transitions, indicating that the excitation is due to a high collision rate rather than radiation trapping.) We therefore apply equation (6) to the results of our observations to obtain density information.

The [DCN]/[$H^{13}CN$] ratios obtained outside the galactic center region (which will be discussed separately below) range from 0.084 in DR 21 to 0.21 at one of the points in the Ori A strip map. If we take the [HCN]/[$H^{13}CN$] ratio to be about 40[3] in all these regions (Wannier *et al.* 1976), we get [DCN]/[HCN] ratios ranging between 2×10^{-3} and 5×10^{-3}, compared with the interstellar [D]/[H] ratio of 1.8×10^{-5} determined for the region with ~200 pc of the Sun by York and Rogerson (1976). Thus the two-orders-of-magnitude enhancement of [DCN]/[HCN] over [D]/[H] appears to obtain over a large portion of the Galaxy, with only a relatively small source-to-source variation.

The relatively small source-to-source abundance variation apparent in our results provides a basis for testing the validity of some of the suggested explanations for the chemical fractionation of DCN referred to in the Introduction. Solomon and Woolf (1973) pointed out that the binding energy of DCN is 598 $\mathrm{cm^{-1}}$ (or 861 K) greater than that of HCN owing to their different zero-point vibration energies. This leads them to suggest a *thermal equilibrium* abundance

$$[\mathrm{DCN}]/[\mathrm{HCN}] \propto \exp{(\Delta E/T)} , \tag{7}$$

where ΔE is the *net* difference between the difference in binding energy of DCN versus HCN and the corresponding difference in the largest reservoir of hydrogen. If most hydrogen is in molecular form in dense molecular clouds, then $\Delta E = 861\ \mathrm{K} - 405\ \mathrm{K}$, because HD has a 281 $\mathrm{cm^{-1}}$ (or 405 K) greater binding energy than H_2. Thus a key prediction of such thermal equilibrium chemical fractionation schemes (see also Watson 1974 and Watson, Crutcher, and Dickel 1975) is a sensitive dependence of the [DCN]/[$H^{13}CN$] abundance ratio on cloud temperature.

[3] Gottlieb *et al.* (1975) suggest a somewhat lower value, ~25, which would yield [DCN]/[HCN] ratios 1.6 times as great as those used above. Since fractionation only allows us to determine the spatial behavior of the ratio, the exact value of the [$H^{13}CN$]/[HCN] ratio concerns us little in this problem.

In particular, a $\sim$20 percent temperature difference between two clouds ought to produce an order of magnitude difference in the ratio, a predicted effect much larger than any we observe outside the galactic center.

When the dominant formation and destruction of a substance occur by different reactions, its population is determined by the relevant reaction rates which themselves may be only weakly dependent upon temperature. Since DCN could be produced by a variety of reactions (Herbst and Klemperer 1973; Watson 1974; Watson, Crutcher, and Dickel 1975), we shall present only a single illustrative example. Enhancement of DCN might occur due to the transfer of D from H_2D^+ to HCN (Watson, Crutcher, and Dickel 1975). The H_2D^+ abundance will be enhanced relative to H_3^+ by the exothermic reaction

$$H_3^+ + HD \rightarrow H_2D^+ + H_2 + \Delta E' . \tag{8}$$

While the exact value of $\Delta E'$ is not known, it is thought to be large enough (Huntress and Anicich 1976) that at the temperatures of interstellar molecular clouds the reverse of equation (8) proceeds more slowly than other H_2D^+ destruction reactions such as

$$H_2D^+ + CO \rightarrow DCO^+ H_2 , \tag{9}$$

$$H_2D^+ + e^- \rightarrow HD + H \tag{10}$$

(W. Klemperer, private communication). Thus the destruction rate, and hence the population of H_2D^+, is determined by quantities like the relative CO abundance and the fractional ionization of the gas which are insensitive to the kinetic temperature.

Whatever scheme proves to be the dominant DCN abundance enhancement mechanism, the insensitivity of the enhancement to conditions in individual sources is apparent in our observations. Thus the results of our observations are seen to suggest an interstellar [D]/[H] ratio which varies only little from the "local" value over much of the Galaxy.

Although the integrated line intensity ratio obtained in Sgr B2 is only moderately smaller than that in the other sources, the [DCN]/[$H^{13}CN$] abundance ratio is very much smaller. The double nature of the $H^{13}CN$ spectrum with peaks near 45 and 80 km s^{-1} is typical of the saturated self-absorbed feature observed in the spectra of many of the common molecules found in this source (Scoville, Solomon, and Penzias 1975), while the single $\sim$60 km s^{-1} feature of DCN is more typical of rarer species. It is thus clear that the [DCN]/[$H^{13}CN$] abundance ratio is appreciably smaller than the value of 0.06 which one would obtain by use of relation (6) which assumes both lines to be optically thin.

While we have no direct way of evaluating the amount of absorption in the $H^{13}CN$ line, we can compare the $H^{13}CN$ and DCN profiles with similarly shaped profiles in this source. The two isotopic species $C^{32}S$ and $C^{34}S$ are thought to have a 25:1 abundance ratio while the integrated intensity of the double-peaked $C^{32}S$ line is only some 5 times that of the single peaked $C^{34}S$ line (Wilson *et al.* 1976). This result suggests that the true [DCN]/[$H^{13}CN$] abundance ratio is between 2 and 10 times smaller than what one would obtain by assuming the lines to be optically thin. Accordingly we have multiplied the result of relation (6) for Sgr B by 0.3 ± 0.2 to allow for the absorption effect. This yields a [DCN]/[HCN] abundance ratio of 0.018 ± 0.012, in contrast to 0.06 ± 0.014 without saturation correction.

IV. CONCLUSIONS

Sagittarius B is seen to have a [DCN]/[$H^{13}CN$] relative abundance ratio which is strikingly lower than that in the other sources investigated. A portion of this effect may be due to relative enhancement of $H^{13}CN$ owing to a higher than average [^{13}C]/[^{12}C] abundance in this source. From a variety of measurements, however, it appears that the [^{13}C]/[^{12}C] abundance in Sgr B is no more than a factor of 2 above the galactic average for dense molecule clouds (Wannier *et al.* 1976; Wilson *et al.* 1976), indicating that the relatively low [DCN]/[$H^{13}CN$] ratio observed in the source reflects a corresponding [DCN]/[HCN] ratio which is lower than that of the other sources.

Since we have concluded above that the [DCN]/[HCN] ratio is insensitive to the physical conditions existing in a particular source, we interpret the low [DCN]/[HCN] ratio to indicate a low [D]/[H] ratio in this source. Sagittarius B is distinguished from the other DCN sources by its location near the galactic center, in the portion of the Galaxy where the greatest amount of stellar activity has taken place and where the interstellar matter contains the greatest proportion of material that has been processed through stars (Reeves 1975). A relatively low proportion of deuterium in this region supports the conclusion that stellar processing leads to a destruction of deuterium (Reeves 1974). Colgate (1973, 1974) and Hoyle and Fowler (1973) have suggested that deuterium could be produced by spallation in strong shock waves generated by explosive events such as supernovae. If such processes were a principal source of deuterium, one would expect an increased deuterium abundance to exist in the central region of the Galaxy owing to its greater stellar activity, the opposite of what is observed. These models were presented as an alternative to nucleosynthesis during the early expansion of a hot big-bang universe as the most important site for the formation of the present Galactic deuterium (Wagoner 1973).

The validity of the conclusions based upon the arguments and data presented above can be tested by additional observations and theoretical investigation. A detection or meaningful upper limit ($T_A \geqslant 0.05$ K) to DCN emission from Sgr A_{CO} would be most helpful since our interpretation depends upon a single source near the galactic center. This could be achieved with a relatively moderate effort once the appropriate cryogenically cooled mixer-receiver and broad-band spectrometer now under construction are completed. This equipment might also produce better data in regions far from the galactic center in order to determine the variation of DCN abundance with metallicity, avoiding the theoretical complication discussed below. Prospects for the success of such a project do not look promising, however. We have searched for CO line emission from the metal-poor H II region NGC 2359, S298, located 15.3 kpc from the galactic center (Georgelin and Georgelin 1970). Within the sensitivity of our search, $\leqslant 0.5$ K corrected antenna temperature, no evidence of line emission was found. This is, to our knowledge, the first H II region in our Galaxy found to be completely devoid of CO line emission, and suggests that millimeter-wave molecular line studies will continue to be restricted to more metal-rich regions.

Present theoretical treatments of interstellar metal enrichment (e.g., Ostriker and Tinsley 1975) generally assume the return of material to the interstellar medium in each stellar generation to occur in a time much shorter than the time scale over which the interstellar metallicity evolves. Such an approximation is clearly appropriate in the solar neighborhood where the dominant portion of the astrated interstellar gas has come from the ejecta of massive stars. In the galactic center region, however, the gas contributed by low-mass stars is no longer negligible. Thus, for a model in which the interstellar gas near the galactic center is predominantly composed of material whose most recent astration occurred in a low-mass star, the fraction of unreprocessed ejecta from high-mass stars would be lower near the galactic center than in the solar neighborhood. A substance which is produced during ejection from massive stars and is destroyed by astration would then have a reduced abundance in the galactic center. While such a model seems inconsistent with our present understanding of Galactic evolution (J. Ostriker, private communication), an evaluation of the consequences of mass loss by low-mass stars would serve to clarify the situation.

V. SUMMARY

We interpret our observations as reflecting the existence of deuterium on a galactic scale. The general uniformity of our results in the outer portions of the Galaxy suggests that the locally observed [D]/[H] ratio of $\sim 1.8 \times 10^{-5}$ (York and Rogerson 1976) is typical of a wide region of the Galaxy. The observed decrease in the [DCN]/[HCN] ratio near the galactic center reflects a corresponding but presumably much greater decrease in the [D]/[H] ratio. Although some portion of the remaining deuterium in this region may be of stellar origin (Audouze *et al.* 1976), we ascribe the decrease in deuterium abundance toward the galactic center to a net destruction of deuterium by stellar processing in the Galaxy. The elimination of stellar activity as the principal source of the observed deuterium leads to the conclusion that this deuterium is of pregalactic and hence cosmological origin.

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REFERENCES

Audouze, J., Lequeux, J., Reeves, H., and Vigroux, L. 1976, preprint.
Colgate, S. A. 1973, *Ap. J. (Letters)*, **181**, L53.
———. 1974, *Ap. J.*, **187**, 321.
Geiss, J., and Reeves, H. 1972, *Astr. Ap.*, **18**, 126.
Georgelin, Y. P., and Georgelin, Y. M. 1970, *Astr. Ap.*, **6**, 349.
Gott, J. R., Gunn, J. E., Schramm, D. N., and Tinsley, B. M. 1974, *Ap. J.*, **194**, 543.
Gottlieb, C. A., Lada, D. J., Gottlieb, E. W., Lilley, A. E., and Litvak, M. M. 1975, *Ap. J.*, **202**, 655.
Green, S., and Thaddeus, P. 1974, *Ap. J.*, **191**, 653.
Herbst, E., and Klemperer, W. 1973, *Ap. J.*, **185**, 505.
Hoyle, F., and Fowler, W. 1973, *Nature*, **241**, 384.
Huntress, W. T., Jr., and Anicich, V. G. 1976, *Ap. J.*, in press.
Jefferts, K. B., Penzias, A. A., and Wilson, R. W. 1973, *Ap. J. (Letters)*, **179**, L57.
Linke, R. A., Goldsmith, P. F., Wannier, P. G., Wilson, R. W., and Penzias, A. A. 1977, submitted to *Ap. J.*
Liszt, H. S. 1973, Ph.D. thesis, Princeton University (see also Penzias 1975, p. 386).
Liszt, H. S., and Linke, R. A. 1975, *Ap. J.*, **196**, 709.
Maki, A. 1974, *J. Phys. Chem. Ref. Data*, **3**, 221.
Ostriker, J. M., and Tinsley, B. M. 1975, *Ap. J. (Letters)*, **201**, L51.
Penzias, A. A. 1975, in *Atomic and Molecular Physics and the Interstellar Matter*, ed. R. Balian, P. Encrenaz, and J. Lequeux (Amsterdam: North-Holland).
Penzias, A. A., Jefferts, K. B., and Wilson, R. W. 1971, *Ap. J.*, **165**, 229.
Phillips, T. G., Jefferts, K. B., and Wannier, P. G. 1974, *Ap. J. (Letters)*, **192**, L153.
Reeves, H. 1974, *Ann. Rev. Astr. Ap.*, **12**, 1974.
———. 1975, in *Atomic and Molecular Physics and the Interstellar Matter*, ed. R. Balian, P. Encrenaz, and J. Lequeux (Amsterdam: North-Holland).
Scoville, N., Solomon, P. M., and Penzias, A. A. 1975, *Ap. J.*, **201**, 352.
Solomon, P. M., Penzias, A. A., Jefferts, K. B., and Wilson, R. W. 1973, *Ap. J. (Letters)*, **185**, L63.
Solomon, P. M., and Woolf, N. J. 1972, *Ap. J. (Letters)*, **180**, L89.
Wagoner, R. V. 1973, *Ap. J.*, **179**, 343.
Wannier, P. G., Penzias, A. A., Linke, R. A., and Wilson, R. W. 1976, *Ap. J.*, in press.
Watson, W. D. 1973, *Ap. J. (Letters)*, **181**, L129.
———. 1974, *Ap. J.*, **188**, 35.
Watson, W. D., Crutcher, R. M., and Dickel, J. R. 1975, *Ap. J.*, **201**, 102.
Wilson, R. W., Penzias, A. A., Jefferts, K. B., and Solomon, P. M. 1973, *Ap. J. (Letters)*, **179**, L107.
Wilson, R. W., Penzias, A. A., Jefferts, K. B., Thaddeus, P., and Kutner, M. L. 1972, *Ap. J. (Letters)*, **176**, L77.
Wilson, R. W., Penzias, A. A., Wannier, P. G., and Linke, R. A. 1976, *Ap. J.*, in press.
York, D. G., and Rogerson, J. B. 1976, *Ap. J.*, **203**, 378.

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