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CN ROTATIONAL EXCITATION

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ABSTRACT

We report the results of a search for new lines of sight in which to study the CN excitation and a statistical analysis of all the excitation temperatures measured using interstellar CN. This data set strongly confirms that the cosmic background radiation (CBR) is the dominant contributor to the excitation of CN, and demonstrates the homogeneity of the CBR. Thirty-five observations is a sufficiently large sample to look for the presence of systematic effects in the CN excitation. The weighted average of the CN excitation temperatures exceeds the $T_{\rm CBR}$ obtained by *COBE* and the Canadian rocket by 82 ± 30 mK. With the aim of looking at the origin of this difference, we have considered in detail the known mechanisms that could contribute to exciting the CN molecule. None of the data necessary to quantify these mechanisms are of sufficient quality to provide a clean explanation of the observed difference.

Subject headings: cosmic microwave background — ISM: general — ISM: molecules

1. INTRODUCTION

Over the past 2 decades several experiments of increasing sensitivity have been carried out to search for anisotropies and spectral distortions of the cosmic background radiation (CBR) which might help in understanding phenomena such as galaxy formation. Recent measurements from the *COBE* satellite (Mather et al. 1990) and from a Canadian rocket (Gush, Halpher, & Wishnow 1990) in the millimeter and submillimeter wavelength range have determined the shape of the CBR spectrum and found it to be very nearly a perfect blackbody. In the following, we refer to *COBE* and Gush results as the space observations. The derived temperatures, 2.735 ± 0.06 K and 2.736 ± 0.01 K respectively, are very close but ~2% below the most precise measurements obtained at 2.64 mm from CN observations toward ζ Ophiuchi (Crane et al. 1989).

This paper reports results from an extensive program to search for new lines of sight in which to study the CN excitation. The original purpose of the search was to verify the precise result toward ζ Oph. When the *COBE* results became known, the interest turned toward trying to understand an apparent difference between the two results. It should be emphasized that the CBR is the main contributor to the rotational excitation of CN. Therefore the data and results presented here make one of the strongest arguments for the homogeneity of the radiation field.

A careful review of the literature revealed that almost all the ground based $T_{\rm exc}$ measurements of interstellar CN, which in the absence of local excitation, would coincide with $T_{\rm CBR}$, are systematically greater than the space observations. In order to investigate this apparent discrepancy we have considered a statistically significant sample of measurements of the CN excitation temperature to search for systematic effects that could be responsible for the discrepancy. In addition to the sample collected from the literature, we have observed the CN absorption line system at 3875 Å toward 10 new stars.

Since all the available data are consistent with an excess of the $T_{\rm exc}$(CN) at 2.64 mm with respect to the space observations, we might conclude that some local pumping mechanism, present in all the observed clouds, contributes with the CBR photons to exciting the rotational levels of the CN molecule. We define the excitation temperature of the observed transitions, measured from the optical data, such that

$$T_{\rm exc}({\rm CN}) = T_{\rm CBR} + T_{\rm loc}$$

where $T_{\rm loc}$ is the contribution due to local excitation mechanisms. These local excitation effects could be determined from a measurement of CN emission at 2.64 mm in the clouds studied (Crane et al. 1989; Palazzi et al. 1990). Since it is well known (Thaddeus 1972; Black 1988) that the most effective local mechanism is electron collisions, when no millimeter CN data are available, a determination of the electron density (n_e) in a cloud combined with the knowledge of the electron cross section is an alternative means of estimating the local contribution to the CN excitation.

Assuming that the true value of the $T_{\rm CBR}$ is the one found from the space observations and that the $T_{\rm loc}$ is the excess in the measured $T_{\rm exc}$(CN), Black & van Dishoeck (1991) have derived the electron density in some observed clouds with accurate data on CN. From their results it turns out that for more than 70% of the cases studied the electron densities estimated from the model are bigger than the ones derived from millimeter observations of CN.

The approach in this work is different from that of Black & van Dishoeck (1991) in that we do not assume an origin for the excess excitation temperature. We attempt to understand if there are any observable quantities which would indicate the origin of the excess excitation over the CBR. Using available data for electron densities, H_2 densities, and other parameters, we find that none of the standard approaches to understanding

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the excess can be shown to explain the observed CN excitation temperature. We emphasize that this does not mean that none of the mechanisms considered are ruled out, but that the data available are not adequate to demonstrate it.

The most common method of estimating the electron density, assuming that the ionization equilibrium is determined by photoionizations and recombinations only, is to use the Ca I to Ca II abundance ratio. In this work we applied this method to the stars of our sample to search for the expected correlation between the derived electron densities and T_{exc}(CN). No correlations have been found. We will discuss some implications in the final section of the paper.

Another possible local effect that could contribute to CN excitation is the radiation due to dust present in the cloud. We find that whatever the temperature of the dust in the cloud, it will never produce a radiation field that can account for the observed discrepancy between the space observations and the CN results.

In the following section we give details on the construction of the data sample, with particular discussion of our observations and relative analysis. In § 3 we discuss the local effects such as electron and neutral collisions and the radiative effects such as diffuse and local starlight and IR dust radiation. Section 4 is the final section in which we discuss the results.

2. DATA SAMPLE

The data discussed here come from the following sources: (1) high-resolution spectroscopy in the wavelength region of the (0, 0) $B^2\Sigma$–$X^2\Sigma$ absorption-line system of the CN molecule (3875 Å) toward 10 new lines of sight; (2) optical data on interstellar molecules taken from the literature; millimeter measurements of our own and those found in the literature.

2.1. *High-Resolution Spectroscopy Observations*

The high-resolution spectra were obtained at the 1.4 m Coudè Auxilliary Telescope of the European Southern Observatory on La Silla in 1990 May. The configuration of CCD detector plus long camera provided a resolution of ∼120,000 at the CN λ3875 wavelength, each pixel sampling 17.01 mÅ of the spectrum.

The observed stars were selected from a sample obtained during previous observing runs (1988 June, October, and December) with the primary purpose of searching for new diffuse interstellar clouds containing the optical absorption features of either CH, CH^+, and CN (Penprase et al. 1992). A particular aim was to find new candidates well suited to study the CBR excitation of the rotational states of CN at 2.64 mm. In our search we detected 30 stars showing CN absorption lines. For the present work we decided to study the ones with a measured $R(0)$ equivalent width greater than 3 mÅ to be sure that the CN column density in the cloud was large enough to provide an accurate (∼15%) determination of the excitation temperature of the molecule.

We started the analysis of our data using the standard procedure to reduce spectra. For each frame we subtracted the bias and divided by the nightly flat field. Then each CCD row showing the CN absorption lines was searched for cosmic rays, and these were eliminated by hand when well distant from the lines. At the end we summed only the rows with higher S/N to obtain the clean spectra. Figure 1 shows the spectra of the 10 stars.

The next step was to determine the excitation temperature of the CN molecule T_{exc}(CN) from our data. T_{exc}(CN) can be derived using the Boltzmann equation

$$\frac{N(i)}{N(j)} = \frac{g_i}{g_j} \exp\left(-\frac{h\nu}{kT}\right),$$

where $N(j)$ and $N(i)$ are the column densities, g_j and g_i are the statistical weights of the lower and upper rotational states, and T is the excitation temperature of the molecular states involved. In the limit of unsaturated absorption the column densities can be directly determined from the integrated intensity, i.e., the equivalent width, of an absorbing line using the relation

$$W_\lambda = \int \frac{I_0 - I_\lambda}{I_0} d\lambda = 8.85 \times 10^{-21} N_i f_{ij} \lambda^2 ,$$

where I_λ is the intensity in the line, I_0 is the intensity in the adjacent continuum, λ is the wavelength of the absorption line in microns W_λ is in angstroms, N_j is in cm^{-2}, and f_{ij} is the oscillator strength of the transition.

To determine the equivalent width of the CN lines in our spectra we selected a region around each line in such a way that a fit could be done using a Gaussian profile and a sloping continuum. The derived parameters for the Gaussians were then used to determine the equivalent widths. Since we have more than one spectrum for each star, we applied this porcedure to all the CN absorption lines for each spectrum, and then we made a weighted average of the equivalent widths to find the most probable values. The results are reported in Table 1. The quoted errors are the standard deviation of the individual values around their mean. The uncertainty due to the continuum placement are also included since the procedure determines both continuum and line parameters simultaneously.

The relationship between equivalent width and column density given above would become nonlinear if saturation

TABLE 1

OUR CN OBSERVATIONS

Star	Names	$W_\lambda R(0)$(mÅ)	$W_\lambda R(1)$(mÅ)	$W_\lambda P(1)$(mÅ)	b(km s^{-1})	T_{exc}(K)
HD 73882	...	34.83 ± 1.93	17.31 ± 0.55	10.23 ± 0.42	1.06 ± 0.09	2.75 ± 0.23
HD 147933a	ρ Oph A	6.11 ± 0.48	2.08 ± 0.67	1.05 ± 0.59	0.84 ± 0.22	2.94 ± 0.48
HD 147933b	ρ Oph B	6.85 ± 0.43	2.12 ± 0.67	1.38 ± 0.66	0.84 ± 0.22	2.86 ± 0.43
HD 148184	χ Oph	3.45 ± 0.31	1.03 ± 0.47	0.46 ± 0.47	1.24 ± 0.42	2.78 ± 0.61
HD 148379	...	1.83 ± 0.47	0.61 ± 0.67	0.46 ± 0.66	1.48 ± 0.45	3.17 ± 1.73
HD 149404	...	7.73 ± 0.43	2.48 ± 0.60	1.34 ± 0.59	0.67 ± 0.30	2.77 ± 0.33
HD 150136	...	1.93 ± 0.54	0.92 ± 0.59	0.15 ± 0.54	1.16 ± 1.00	3.29 ± 1.58
HD 152236	ζ^1 Sco	6.09 ± 0.32	2.09 ± 0.60	0.74 ± 0.59	0.65 ± 0.40	2.80 ± 0.43
HD 169454	...	25.10 ± 0.70	15.50 ± 0.88	10.85 ± 0.83	0.64 ± 0.17	2.84 ± 0.18
HD 170740	...	13.60 ± 0.43	6.68 ± 0.61	3.82 ± 0.60	0.84 ± 0.20	3.49 ± 0.22

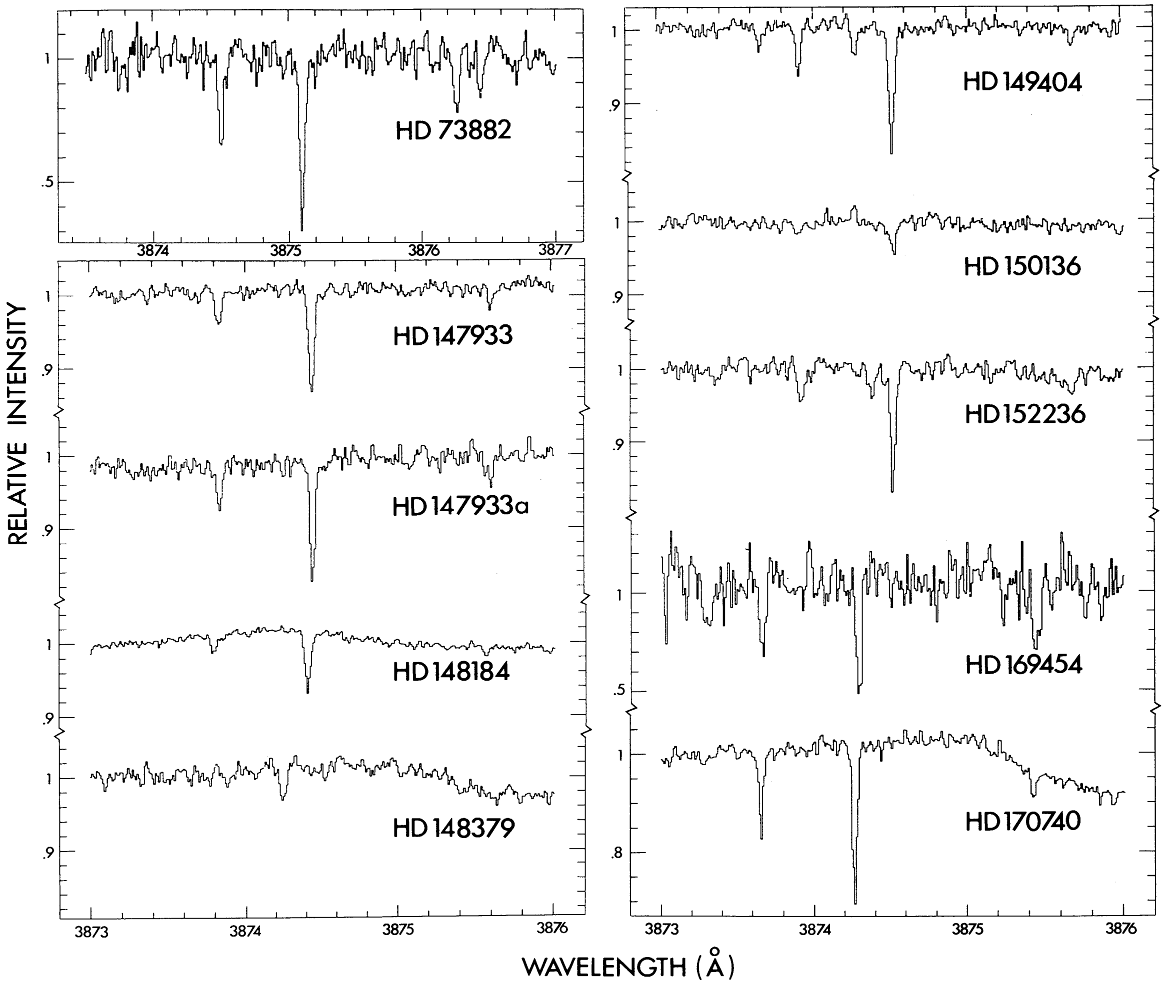

FIG. 1.—Optical spectra of interstellar CN absorption line system at 3875 Å toward the stars observed by the authors. The wavelength scale refers to the local standard of rest (LSR).

effects are present. In order to correct for saturation, an accurate knowledge of the true profile of the CN absorption line is required. Unfortunately, this is very difficult to acquire at the resolution of our optical observations.

We made the assumption that the CN has a Gaussian velocity dispersion and that the lines we observed are a convolution of the instrumental and the intrinsic line profile. The velocity width parameters, b, derived for each cloud from the fit to the $R(0)$ line are also reported in Table 1. It should be noted that since the $R(0)$ line is the most affected by saturation, the fact that it is a blend of two lines separated of ~ 3.9 mÅ could in some cases make the derived b value bigger than the true one (van Dishoeck & Black 1989).

The equivalent widths corrected for saturation were used to compute the CN column densities and the CN excitation temperatures at 2.64 mm using the above-mentioned formulae. The results obtained are reported in the last column of Table 1. The uncertainties associated with the temperature are derived from the standard procedures for propagation of errors (Bevington 1969).

Three stars included in Table 1 have been previously observed by other authors. Federman, Danks, & Lambert (1984) detected the CN absorption-line system in the stars HD 147933 and HD 148184, while Crawford (1990a) observed only the $R(0)$ and $R(1)$ CN line in the star HD 152236. The results of these observations have not been included in our sample because Federman did not include any errors in the equivalent widths, and because Crawford reported results only for $R(0)$ and $R(1)$.

2.2. *Selected Stars from the Literature*

In the past 2 decades many measurements of the T_{CBR} have been performed using interstellar CN. Many different lines of sight have been investigated and some of them (ζ Oph, ζ Per) by several different groups. In Table 2 we list for the stars that we have taken from the literature, the relative equivalent widths of the CN lines, the velocity width parameter b and the CN excitation temperature, corrected only for saturation. The data in Table 2 generally include results from observations made with high resolution ($>60,000$) and made with modern instruments. For sight lines which have been observed by many groups we include only data with the smallest errors.

For each of the stars listed in Tables 1, and 2, we looked for published measurements of Ca I and Ca II (H and K), H I, H_2, and millimeter CN with the aim of deriving the electron and neutral densities and determining the collisional contribution to the CN excitation. All the ancillary data that we could collect from our search are reported in Table 3. We note that in

TABLE 2

CN OBSERVATIONS FROM THE LITERATURE

Star	Names	$W_\lambda R(0)$ (mÅ)	$W_\lambda R(1)$ (mÅ)	$W_\lambda P(1)$ (mÅ)	b (km s^{-1})	T_{exc} (K)	References
HD 21483	...	44.05 ± 0.28	23.04 ± 0.20	13.79 ± 0.17	1.29 ± 0.03	2.81 ± 0.03	1, 2
HD 23180	*o* Per	4.69 ± 0.10	1.39 ± 0.06	0.69 ± 0.06	1.30 ± 0.4	2.78 ± 0.07	3
HD 24398	ζ Per	8.99 ± 0.02	2.89 ± 0.02	1.30 ± 0.02	1.25 ± 0.02	2.79 ± 0.03	4
HD 26571	...	21 ± 3	11 ± 4	8 ± 3	0.70	3.22 ± 0.96	5
HD 29647	...	62 ± 3	46 ± 3	31 ± 3	1.40 ± 0.2	2.90 ± 0.08	6
HD 53367	...	12.2 ± 0.6	5.8 ± 1.1	1.7 ± 0.4	0.95	2.75 ± 0.25	7
HD 62542	...	26.45 ± 0.50	18.35 ± 0.40	11.60 ± 0.40	0.69 ± 0.1	3.30 ± 0.20	8
HD 63804	...	28.8 ± 6.6	9.3 ± 1.8	4.0 ± 1.2	0.70	1.67 ± 0.91	7
HD 80077	...	38.0 ± 1.5	18.6 ± 3.5	10.70 ± 2.5	0.95	2.90 ± 0.20	2, 7
HD 94413	...	21.6 ± 3.0	13.5 ± 1.9	11.6 ± 0.7	0.40	1.77 ± 1.07	7
HD 110432	...	4.2 ± 0.6	1.0 ± 0.3	0.5 ± 0.08	1.0	2.49 ± 0.21	7
BD −14°5037 ...	...	13.0 ± 3.5	10.0 ± 3.5	6.0 ± 3.5	0.40	4.06 ± 3.70	7
HD 147084	*o* Sco	13.2 ± 1.3	7.7 ± 3.0	2.9 ± 2.0	1.0	3.60 ± 1.02	7
HD 147343	...	18.2 ± 3.4	9.7 ± 2.7	6.0 ± 2.3	0.80 ± 0.2	3.52 ± 0.91	9
HD 147701	...	24.3 ± 2.1	14.1 ± 1.8	7.5 ± 1.5	0.80 ± 0.2	3.13 ± 0.42	9
HD 147889	...	36.7 ± 1.5	20.0 ± 1.4	10.2 ± 1.0	1.40 ± 0.3	3.19 ± 0.18	9
HD 149757	ζ Oph	7.75 ± 0.04	2.45 ± 0.02	1.25 ± 0.02	0.88 ± 0.2	2.796 ± 0.013	10
HD 154368	...	24.62 ± 0.13	15.12 ± 0.11	9.74 ± 0.09	0.65 ± 0.01	2.87 ± 0.08	11
HD 161056A	...	8.7 ± 1.0	1.1 ± 1.0	2.0 ± 1.0	1.0	2.22 ± 0.55	7
HD 161056B	...	15.6 ± 1.0	4.7 ± 1.0	3.0 ± 1.0	1.0	2.65 ± 0.27	7
HD 206267	...	22:	8:	...	...	3.19:	12
HD 207198	...	15:	4:	...	...	2.70:	12
HD 210121	...	23.4 ± 2.0	10.0 ± 0.9	4.9 ± 0.9	1.0	2.80 ± 0.20	2, 7
HD 210839	λ Cep	7:	3:	...	...	3.54:	12
... .	TY CrA	21.00 ± 2.75	13.00 ± 2.75	8.0 ± 4.5	0.60 ± 0.3	3.10 ± 1.05	13

REFERENCES.—(1) Meyer et al. 1989; (2) Black & van Dishoeck 1991; (3) Meyer & Jura 1985; (4) Kaiser & Wright, 1990; (5) Crawford 1990; (6) Crutcher 1985; (7) Gredel, van Dishoeck, & Black, 1991; (8) Cardelli, et al. 1990; (9) Cardelli, & Wallerstein, 1986; (10) Crane, et al. 1989; (11) Palazzi 1990; (12) Chaffee, & Dunham, 1979; (13) Cardelli & Wallerstein, 1989.

some cases, marked with an asterix in the table, we computed the H_2 column density using the relation between H_2 and CH (Mattila 1986) $N(H_2) = 2.1 \times 10^7 N(CH) + 2.2 \times 10^{20}$, and that we adopted $N(H) = N(H\,I) + 2N(H_2)$.

2.2.1. HD 24398 (ζ Per)

For the HD 24398 cloud, the data reported in Table 2 are those published by Kaiser & Wright (1990). We have used their value for the equivalent widths and the velocity parameter b to derive the T_{exc}(CN) and the resulting value is 2.816 ± 0.03 K instead of the published one 2.79 ± 0.03 K. Moreover, from the calcium data (White 1973), we derive a correction for local excitation of 0.013 K instead of the 0.04 K used by Kaiser & Wright. The difference between theses two results depends on the adopted values mostly for the kinetic temperature of the cloud and hence for the recombination coefficient $\alpha (\alpha \propto T_{Kin}^{-0.7})$ and less importantly on the photoionization rate Γ.

We note that if our values for T_{exc}(CN) and T_{loc} for the HD 24398 cloud are correct, then the resulting T_{CBR} is 2.80 ± 0.04, exactly the same as for the ζ Ophiuchi cloud.

2.2.2. HD 21483

For the HD 21483 cloud, the values reported are from Meyer, Roth, & Hawkins (1989). Since, as we mentioned above, the most precise result for T_{exc}(CN) for each line of sight have been included in Table 2, we note that for this cloud a more precise result for T_{exc}(CN) than the one reported has been published by Black & van Dishoeck (1991), T_{exc}(CN) = 2.81 ± 0.03 K. However, we did not include this last result in Table 2 because the relative values for the equivalent widths have not been published.

2.2.3. HD 23180 (*o* Per)

For the HD 23180 cloud, a T_{exc}(CN) = 2.78 ± 0.07 K has been measured by Meyer & Jura (1985). They applied a correction due to a local excitation of 0.085 K about a factor of 7 bigger than the value we obtain from our analysis of the calcium data. Also in this case, as for the HD 24398 (ζ Per) cloud, we impute the discrepancy between the different results to the values adopted for the kinetic temperature of the cloud and for the Γ parameter.

2.2.4. HD 73882, HD 149404, HD 169454 and HD 170740

In compiling Table 2, we have not included results from other observations of the stars in Table 1. Four stars in Table 1, HD 73882, HD 149404, HD 169454, HD 170740, were also observed by Gredel, van Dishoeck, & Black (1991).

Since for many of the stars of their sample, Gredel et al. have used CN observations of the violet system at 3875 Å and of the red system at 7900 Å in deriving the saturation corrections, they adopted b values that yielded the same CN column densities for both systems. In comparing our results to theirs, we find no evidence for systematic differences in the equivalent widths or b values.

In particular, for the four stars in common with Gredel et al., the derived temperatures agree within the errors for the stars HD 73882 and HD 169454. For HD 149404, T_{exc}(CN) derived by Gredel et al. is 2.2 K, much lower than our derived value 2.77 ± 0.33 K. The difference can be explained by the fact that they did not measure the b parameter from the CN observations but adopted the value derived from ^{13}CO observations which is lower than the one we determined from our CN observations. For HD 170740, our measured T_{exc}(CN) does not agree with the result of Gredel et al. In this case we adopted the same b value for the analysis, the differences are in the measured equivalent widths of the CN lines. We have a larger number of spectra on this star than Gredel et al. and this allows a more certain determination of the CN equivalent widths. We have included only our results for these four stars

TABLE 3

ANCILLIARY DATA

Star (1)	$E(B-V)$ (2)	Distance (pc) (3)	W_λ Ca I (mÅ) (4)	W_λ Ca II H (mÅ) (5)	W_λ Ca II K (mÅ) (6)	$b_{\mathrm{Ca\,II}}$ (km s^{-1}) (7)	Reference (8)	T_{Kin} (K) (9)	log N(H I) (cm^{-2}) (10)	log $N(H_2)$ (cm^{-2}) (11)	Reference (12)	n_e (cm^{-3}) (13)	n_{H_2} (cm^{-3}) (14)	T_R^* (mK) (15)
HD 21483	0.58	...	...	145.0	90.0	...	1	25	...	20.81*	1	...	...	43
HD 23180	0.30	239	1.46 ± 0.46	82.0	58.0	2.63	2	25	20.90	20.61	19	0.03	200	1
HD 24398	0.32	394	0.86 ± 0.29	55.0	36.0	2.14	2	30	20.81	20.67	20	0.04	210	4
HD 26571	0.77	140	≤3	90.0	...	3.0	3	25	19.65	20.81*	3	0.098	1300	152
HD 29647	1.04	140	≤5	280.0	150.0	15.0	4	10	20.16	21.54	4	0.002	800	116
HD 62542	0.33	400	≤0.6	43.2	23.5	5.2	5, 6	55	...	20.98*	5	0.074	1460	211
HD 73882	0.71	398	...	...	...	...	7	25	...	20.94*	13	...	...	7
HD 80077	1.52	3000	...	...	...	...	...	25	...	21.40*	21	...	...	...
HD 147343	0.64	167	8.4 ± 2.3	97.8	≤55	4.5	8	40	21.43	20.78	8	0.14	1000	136
HD 147701	0.73	220	4.0 ± 1.7	≤44.0	≤35.0	4.5	8	40	21.50	20.90	8	0.14	1000	132
HD 147889	1.09	206	5.8 ± 1.5	46.0	36.0	4.5	8	40	21.46	21.37	21	0.075	2000	115
HD 147933a	0.48	170	4.5 ± 0.6	46	39	1.6	9, 10	45	21.54	20.57	19, 20	0.18	10000	9
HD 148184	0.44	134	4.0 ± 4.0	51	27	...	11	45	21.15	20.63	19, 20	0.077	1500	1
HD 148379	0.74	1400	...	470	280	...	12	25	...	20.41*	13	...	...	4
HD 149404	0.68	1400	8.45	...	...	...	13	25	21.40	20.89*	13, 22	...	...	4
HD 149757	0.33	138	1.6 ± 0.4	35.0	21.0	7.03	2, 9	30	20.72	20.64	20	0.17	289	5
HD 150136	0.49	...	...	300	220	...	14	25	...	...	...	...	...	6
HD 152236	0.68	1900	0.2	370	230	...	12	25	21.74	20.67*	22, 23	...	...	6
HD 154368	0.82	800	...	...	...	...	...	25	...	21.28*	20	...	...	75
HD 169454	1.14	1700	0.8	690	360	...	12	15	≥19.95	21.16*	16, 21	...	...	78
HD 17040	0.48	...	...	75	41	...	10	25	...	20.81*	13	...	...	82
HD 206267	0.51	800	≤3	236.0	159.0	8.4	15	40	21.15	20.91	15	0.02	1000	...
HD 207198	0.61	1017	15	277.0	186.0	10.0	7, 15	40	21.15	21.01	15	0.09	1000	...
HD 210121	0.32	210	2.0 ± 1.0	...	...	...	16	20	...	20.98*	16	...	...	22
HD 210839	0.56	800	9.2	215	149	7.2	15, 17	40	21.11	20.78	20	0.065	1000	...
TY CrA	0.48	...	≤6	27.0	...	≥5	18	25	...	21.10*	18	0.026	1000	162

REFERENCES.—(1) Cohen 1973; (2) White 1973; (3) Crawford 1990a; (4) Crutcher 1985; (5) Cardelli et al. 1990; (6) Gredel, van Dishoeck, & Black 1992; (7) Deutschmann, Davis, & Schild 1974; (8) Cardelli & Wallerstein 1986; (9) Lambert & Danks 1986; (10) Spitzer, Epstein, & Heu 1950; (11) Frisch 1979; (12) Cohen 1975; (13) Penprase et al. 1991; (14) Buscombe & Kennedy 1968; (15) Chaffee & Dunham 1979; (16) de Vries & van Dishoeck 1988; (17) Federman & Hobbs 1983; (18) Cardelli & Wallerstein 1989; (19) Savage et al. 1977; (20) Bohlin, Savage, & Drake 1978; (21) Black & van Dishoeck 1991; (22) Shull & van Steenberg 1985; (23) Crawford 1990b.

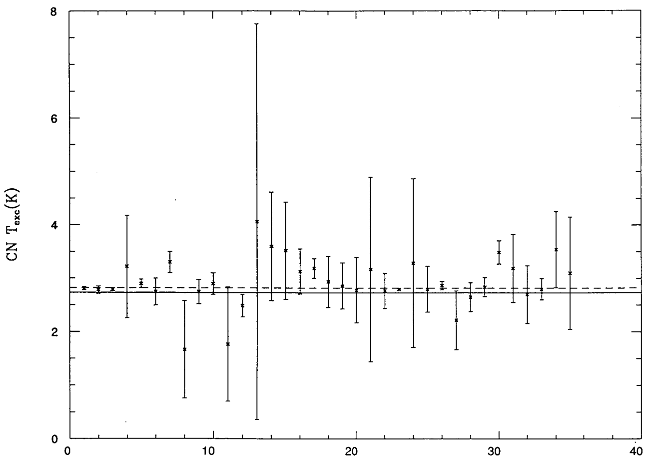

FIG. 2.—Measured T_{exc}(CN) with the associated 1 σ errors vs. increasing HD number of the observed stars. The data are from Tables 1 and 2. The solid line represents the space result for T_{CBR}, $T = 2.735 \pm 0.020$ K, the dashed line in the weighted average of the T_{exc}(CN) values, $T = 2.818 \pm 0.018$ K.

in the analysis below, because we have a better understanding of the systematic effects in our own data than for Gredel's.

2.3. *CN Excitation Temperature*

As a first comparison between all the CN data available and the recent *COBE* and Gush et al. results, we have plotted (Fig. 2) the T_{exc}(CN) with the relative errors for all the stars of Tables 1 and 2 together with T_{CBR} value of 2.735 K. From a first analysis of Figure 2, it is evident that most values of T_{exc}(CN) exceed the space results. Five of the six values which lie below the solid line in Figure 2 are results from Gredel et al. (1991). This is most likely due to random errors in the measurements of the equivalent widths. The fact that most measurements lie above the space results should not be surprising, since, as mentioned in § 1, there may be some pumping mechanisms at work which may fully or in part be the cause for this excess in the excitation temperature. For instance, for the known dense cloud in the direction of HD 147889, there is likely local excitation.

What is surprising instead is that the weighted mean of our sample (excluding the most well studied case ζ Oph) gives a value $\langle T_{exc}(\mathrm{CN})\rangle = 2.817 \pm 0.022$ K which is in good agreement with the ζ Oph value, 2.796(+0.014; −0.039) K. We have not included the ζ Oph result in the weighted average since this value has a considerably greater weight and an undue influence. We recall that for the ζ Oph sightline, the local effects are negligible and do not contribute substantially to the T_{exc}(CN) (Crane et al. 1989).

The distribution of T_{exc} values found in Figure 2 is what would be expected if the main excitation were from the CBR radiation and there was another contribution of unknown magnitude due to local effects. The weighted average is mostly determined from the few precise measurements which have been chosen a priori to have small local excitation effects.

In order to quantify the difference between the *COBE* and Gush values for T_{CBR} and the CN excitation temperature, we take $T_{CBR} = 2.735 \pm 0.020$ K for the *COBE*/Gush value. The error in this value is our attempt to assess the statistical uncertainties in the measurements and not the calibration or other systematic errors. As consequence we find $T_{exc}(\mathrm{CN}) - T_{space} \simeq 82 \pm 30$ mK where the uncertainty depends on our assumed error in the space results.

3. LOCAL EFFECTS

In order to pursue possible origins of the difference we find above, we have investigated a number of possible physical effects which could give rise to this difference. Electron and neutral collisions may both contribute to the rotational excitation of the CN molecule; in addition radiative effects will be briefly considered. Effects due to multiple unresolved clouds and to uncertainties in the assumption about molecular structure are briefly considered.

3.1. *Electron and Neutral Collisions*

The electron impact is the local process that most likely contributes to the CN excitation in diffuse interstellar clouds (Thaddeus 1972).

The electron density is an important physical quantity which is very difficult to determine directly. The standard procedure for estimating n_e depends on the asumption of ionization equilibrium and the ratio of space densities of an atom in two adjacent states of ionization

$$\frac{n(i+1)}{n(i)}\, n_e = \frac{\Gamma}{\alpha}\,,$$

where Γ is the photoionization rate (s^{-1}) and α is the coefficient of radiative recombination ($\mathrm{s}^{-1}\ \mathrm{cm}^3$).

The use of this method suffers some fundamental difficulties such as the impossibility of directly measuring space densities. If both ionization states are not equally distributed along the line of sight, and this is possible since several clouds could occur, using the column densities in the above relationship results in an average value for n_e.

On the other hand this is one of the few ways in which the electron density can be determined in interstellar clouds. We decided to use the Ca I and Ca II atoms to make the calculation, assuming that both are formed in the same region of the cloud (White 1973).

The quantity Γ is a function of the radiation field intensity, and it depends very strongly on position within the cloud because of extinction of ionizing photons by grains. The values we used are computed using the relation $\Gamma = C \exp(-\gamma A_V)$ (van Dishoeck 1988), where C is equal to the photoionization rate for Ca I due to an unattenuated radiation field (3.4×10^{-10}, from Draine 1978), γ is equal to -1.68 and A_V corresponds to half the reddening of the star considered. The α coefficient is a function of the kinetic temperature (T_{Kin}) of the cloud ($\alpha \propto T_{Kin}^{-0.7}$), and for our purpose we used the values given by Seaton (1951). When T_{Kin} was not available in the literature we assumed a value of 25 K.

Unfortunately, not all the stars in our sample have been observed at the Ca I and Ca II H and K wavelengths, and the available data are often of very poor accuracy. In columns (4), (5), and (6) of Table 3 we report the equivalent widths of the calcium absorption lines in the cases studied (16 with both the measurements). To obtain homogeneous data we recomputed the calcium column densities using the same oscillator line strengths ($f = 1.55$ for Ca I, $f = 0.345$ for Ca II H, and $f = 0.690$ for Ca II K) for all the measurements and therefore n_e using the ionization equilibrium equation. Column (13) of Table 3 reports n_e computed in this way and then uses this to drive the local contribution to the excitation temperature due to electrons ($T_{loc,e}$).

The local excitation can be derived from n_e following the analysis described by Thaddeus (1972); namely, we computed the rate of excitation, C_{01}, from the $J = 0$ level to all the others

TABLE 4

CORRECTED T_{CBR}

Star	T_{exc}(K)	$T_{loc,e}$ (K)	T_{loc,H_2} (K)	T_{CBR} (K)
HD 23180	2.78 ± 0.07	0.009	0.003	2.77 ± 0.07
HD 24398	2.79 ± 0.03	0.013	0.002	2.78 ± 0.03
HD 26571	3.22 ± 0.96	0.030	0.011	3.18 ± 0.96
HD 29647	2.90 ± 0.08	0.000	0.003	2.90 ± 0.08
HD 62542	3.30 ± 0.20	0.028	0.018	3.25 ± 0.20
HD 147343	3.52 ± 0.91	0.047	0.010	3.46 ± 0.91
HD 147701	3.13 ± 0.42	0.049	0.011	3.07 ± 0.42
HD 147889	3.19 ± 0.18	0.026	0.021	3.14 ± 0.18
HD 147933	2.94 ± 0.48	0.073	0.116	2.75 ± 0.48
HD 147933a	2.86 ± 0.43	0.074	0.118	2.67 ± 0.43
HD 148184	2.78 ± 0.61	0.031	0.018	2.73 ± 0.61
HD 149757	2.796 ± 0.013	0.057	0.003	2.74 ± 0.02
HD 206267	3.19:	0.007	0.010	3.17:
HD 207198	2.70:	0.034	0.011	2.65:
HD 210839	3.54:	0.022	0.010	3.51:
TY CrA	3.10 ± 1.05	0.008	0.008	3.08 ± 1.05

using the relation $C_{01} = n_e r_{01}$, with $r_{01} = \langle v\sigma_{01} \rangle$, where v is the kinetic velocity and is σ_{01} the cross section for excitation by electron impact. We employ for r_{01} the values computed by Allison & Dalgarno (1971) for interstellar clouds with the kinetic temperatures reported in column (9) of Table 3. The resulting local excitation is given in column (3) of Table 4.

Neutral particle (mainly H_2) impacts could be another contribution to the rotational excitation of the CN molecule (Thaddeus 1972). To compute the local contribution to the excitation temperature due to neutral collisions (T_{loc,H_2}) we have followed a similar analysis to the one used for electrons in the previous paragraph. In this, of course, we have used a different value for the rate of excitation C_{01}; Black & van Dishoeck (1991) report a rate of $3.8 \times 10^{-11} n(H_2)$ s^{-1} for a kinetic temperature of 20 K. Using the temperature of column (9) of Table 3 and the $n(H_2)$ from the literature (col. [14]) we computed T_{loc,H_2} for neutral impacts. These results are given in Table 4 column (4). The values for $n(H_2)$ given in Table 3 are quite uncertain and represent upper bounds in many cases. The $n(H_2)$ values were taken mostly from the references in Tables 2 or 3.

T_{loc} due to both excitation mechanisms is then used to correct the T_{exc}(CN) in order to obtain T_{CBR}. The resulting values given in Table 4 show that in several cases the T_{loc,H_2} is not negligible with respect to $T_{loc,e}$. Nevertheless the T_{corr} values (T_{corr} is the excitation temperature corrected for the local effects given in Table 4) found are statistically larger than the space result: the weighted average, excluding ζ Oph, is 2.807 ± 0.025 K, greater than T_{CBR}(space) by 2 σ. As we explained above the precise ζ Oph result has a large weight in the average; moreover the local contribution to the CN excitation derived from the calcium analysis is much greater than the upper limit determined by searching for CN emission at 2.64 mm (Crane et al. 1989). In any case, if we include the ζ Oph result in the average we obtain 2.767 ± 0.016 K, which is still greater than the T_{CBR}(space). We assume that the difference between the electron densities determined from calcium and the limit from CN emission is due to uncertainties in the calcium analysis.

A possible explanation for this discrepancy even after correcting for collisional excitation can be that the electron density computed using the calcium absorption lines could be underestimated. In fact,

1. It is very difficult to extract accurate column densities from the Ca II observations, since in many cases the Ca II has more than one component.
2. The Ca II could be present in different regions (less dense) of the interstellar cloud than Ca I and CN so that the computed value of the electron density is a lower limit.
3. If the interstellar cloud is located close to the star, the radiation field would be raised substantially above the assumed value, increasing the actual electron density above the derived value.
4. The ratio of n_e/n_{H_2} seems low for many sources indicating a possible systematic effect in n_e derived from calcium or in the values of n_{H_2}.
5. Similarly an underestimation of n_{H_2} or the H_2- CN cross section may eventually explain the discrepancy under discussion. However, as mentioned above, the values of n_{H_2} given in Table 3 are high in many cases.

A direct way to check these hypotheses is to measure CN emission at 2.64 mm to derive T_{loc}. The mm results are sensitive to any excitation mechanism which heats CN above CBR. We report in column (15) of Table 3 the expected value for the source antenna temperature (T_R^*) derived from the relation (Crane et al. 1989)

$$T_R^* = 0.74\eta_c[1 - \exp(-\tau)]T_{loc} ,$$

where $\eta_c = 1$, the source coupling efficiency, for a source uniformly filling the antenna beam, the optical depth τ is determined from the CN column density $N(1)$ and $T_{loc} = T_{exc}(CN) - T_{space}$, where we assume that the space result is the true T_{CBR}.

We have made two direct observations of CN emission in the directions of ζ Oph and HD 154368 obtaining $T_{loc} \leq 31$ mK and $T_{loc} = 35 \pm 9$ mK, respectively. Surprisingly, the measured ζ Oph value is smaller than the one estimated (Table 4) from the electron density. We do not have any calcium data for HD 154368.

This suggests that observations of CN millimeter emission are needed. There are already indications (Crane et al. 1989; Palazzi et al. 1990; Black & van Dishoeck 1991) that direct measurements of T_{loc} from these millimeter observations (the only true measurements of T_{loc}) are smaller than the values if T_{loc} derived from electrons as discussed above.

The difference between the electron densities derived from optical and those derived from millimeter data could be explained if small-scale structure was present in the interstellar medium. Observations of millimeter CN emission are typically taken with beam sizes of $\simeq 1'$ which is much greater than the optical beam size. If a dense, but small patch ($\leq 1'$) of CN emission lies in the optical path, it would be diluted in the beam of a typical millimeter observation and cause the millimeter results to underestimate the electron density.

However, in the single case where it has been possible to evaluate the small-scale structure has shown no evidence for structure. In particular, a comparison of the CN optical line profile observed toward ζ Oph by Lambert, Sheffer, & Crane (1990) with the CO millimeter line profile of LeBourlot et al. (1989) shows a remarkable similarity in spite of the very different beam sizes of the optical and radio observations. This is evidence against small-scale structure that would compromise the millimeter results vis-a-vis the optical. It would be exceptionally bad luck if the small-scale turbulence and clumpiness in the CN were very much different than for the CO and yet conspired to produce similar line profiles.

In addition, the few optical and ultraviolet studies of interstellar absorption lines toward both components of a resolvable binary (Meyer 1990) have shown that the presence of small-scale structure in the diffuse interstellar medium is more the exception than the rule. For this reason we believe that millimeter observations are the only direct way to get useful information on the local physical processes in the diffuse cloud which could excite CN above the CBR. Nevertheless, such studies may be confounded by small-scale structure in the clouds.

3.2. *Radiative Effects*

Thaddeus (1972) analyzed the most important radiative processes, other than the CBR, that could explain the excitation of CN. We follow his procedure to investigate if radiation could explain the excess CN excitation.

Diffuse Galactic starlight is the first radiative field considered. The result from Thaddeus's analysis is that the excitation rate due to this radiation field is four orders of magnitude less than that required to completely excite CN at 2.64 mm. The diffuse Galactic starlight fails by roughly a factor of 1000 to account for the observed 82 mK. Indeed such a radiation field would have been seen by several experiments and in particular the DMR on *COBE*.

The radiation due to the star beyond the cloud is the second process considered by Thaddeus. If the cloud lies very close to the hot OB star, but usually we do not know the distance, the photons coming from the last scattering surface could cause the CN excitation. If that is the case we would expect either a molecular photodissociation rate which is too large to be compatible with the observed CN abundances or photoexcitation which would give observable emission at 2.64 and 1.32 mm. Thus local starlight is unlikely to be responsible for the discrepancy we find with the space result.

Another radiative process in interstellar clouds could exist that has not been considered by Thaddeus, but that could contribute to the CN excitation. Dust present in the clouds could provide a radiation field with a diluted blackbody spectrum. We assumed that the radiation field we measure using CN (I_{CN}) is given by the sum of the CBR field (I_{CBR}) plus a contribution due to the dust (I_{DUST})

$$I_{CN} = I_{CBR} + \frac{1}{\eta} I_{DUST} ,$$

where η is a dilution factor that should be the same at both wavelengths of the CN measurements, 2.64 and 1.32 mm. We considered four different stars (HD 21483, HD 29647, HD 149757, and HD 154368) toward which the T_{exc}(CN) has been measured both at 2.64 and 1.32 mm, and we used those temperatures to derive the I_{CN} in each case. To derive I_{CBR} we adopted the T_{CBR} resulting from the space data. At this point, for each star, we used temperatures for the dust ranging between 10 and 10^4 K to determine I_{DUST}.

The resulting η(2.64 mm) and η(1.32 mm) in the range of dust temperatures considered never converge to the same value for any of the stars studied. For example, in Figure 3 the values obtained at the two wavelengths for the star HD 154368 are shown. In this case, the values of η converge at a temperature of $T_{DUST} \approx T_{CBR}$ within the uncertainty. This is precisely what is expected if $T_{exc}(CN) \equiv T_{CBR}$. Thus there is no value for T_{DUST} which could be the origin of a radiation field that would explain the observed T_{exc}(CN).

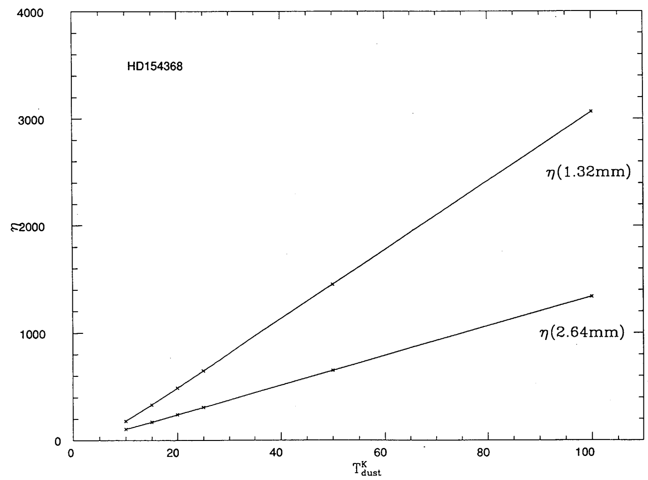

FIG. 3.—η values for the star HD 153468 at the two wavelengths, 2.64 and 1.32 mm, vs. dust temperatures. η is the dilution factor of a blackbody radiation field produced by the dust that could be present in the cloud and should be the same at the two wavelengths (see text for more details).

3.3. *Correlations*

In an attempt to discover if there are any physical processes which might give rise to the difference between the CN excitation temperature and the T_{CBR}(Space), we have looked for possible correlations between T_{exc}(CN) and several quantities. We have not found any significant correlation between T_{exc}(CN) and the Doppler broadening parameter, b (Fig. 4), the reddening E_{B-V}, the electron density n_e (Fig. 5) the distance from the Sun, or the distance from the Galactic center. We note, however, that due to the often larger errors in the parameters, and due to the possibility that more than one parameter may effect T_{exc}(CN), the correlations we have looked at may not show any correlation where one may indeed exist. The need for better data is often all to obvious.

The lack of correlation with the Doppler broadening parameter is important since this is one major source of possible systematic effects. Using too small a Doppler width decreases the T_{exc} whereas too large a value would increase T_{exc}.

If the CN always exists in several small clumps with small b values in each cloud, our estimate of the saturation correction

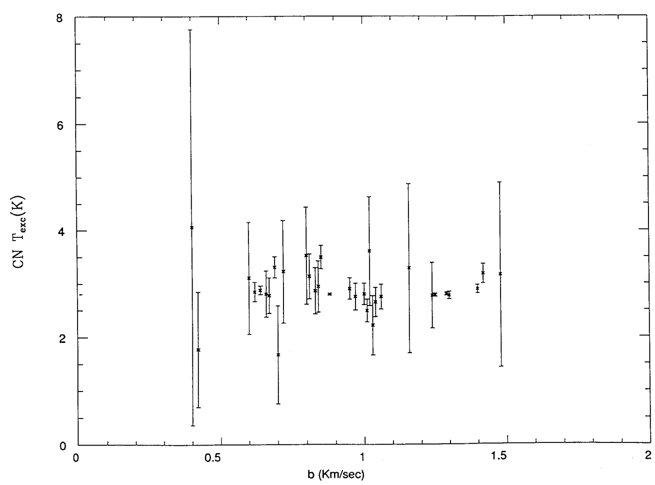

FIG. 4.—T_{exc}(CN) vs. b. It is clear that underestimation or overestimation of the Doppler parameter b does not effect the mean value of T_{exc}(CN).

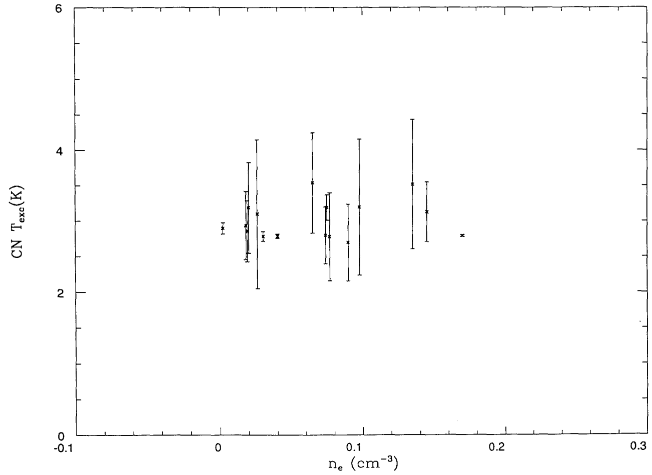

FIG. 5.—T_{exc}(CN) vs. n_e. These two variables are completely uncorrelated although more precise results would strengthen this conclusion.

could be in error. The one case where we can check this, ζ Oph shows almost no difference between the excitation temperature derived for a single cloud model and using the correct two-cloud model which was based on the results of Lambert, Sheffer, & Crane (1990). Thus there does not seem to be a universal problem, but for certain sight lines, such clumping of CN could lead to an overestimate of the excitation temperature.

In the process of searching for correlations, we have found marginal evidence for a dependence of electron density on Galactic distance in the solar vicinity. Even if this is correct, this does not effect the CN excitation.

4. CONCLUSIONS

We have presented an analysis of T_{exc}(CN) for several sight lines. We find the value of T_{exc}(CN) is greater than T_{CBR}(Space) by 82 ± 30 mK. Available data to estimate electron densities and the theory used to predict the excitation of CN by electron collisions are currently not adequate to explain the effect. We have considered possible radiative effects, and these also cannot explain the observed CN excitation. This result is contrary to the assumption of Black & van Dishoeck (1991), who assumed that the excitation of CN over the space results for T_{CBR} was due to electron collisions.

The two best-studied sight lines, ζ Oph and HD 154368, illustrate the problem most effectively. For HD 154368, $T_{exc}(CN) = 2.87 \pm 0.08$ K and if the $T_{CBR} = 2.735$ K, we would expect to find an emission feature at 2.64 mm with a strength of $T_R^* = 75$ mK. The line that is seen has instead a $T_R^* = 19.0 \pm 5.1$ mK (Palazzi et al. 1990). A similar analysis can also be made for ζ Oph although the millimeter result is only an upper limit. Thus these two cases show no evidence for large enough local effects that could be the cause for the difference between T_{exc}(CN) and T_{CBR}.

Considering the other sight lines for which we have collected data, the evidence for local excitation is not conclusive but should be verifiable in some cases with improved observations. The sight line toward HD 147889, is particularly interesting since it should be possible to measure the 2.64 mm emission.

Either a clear explanation of the CN excitation must be found or the temperature of the CBR is greater than 2.735 K. As better data on the local conditions in the molecular clouds becomes available, it is our expectation that the observed excess excitation of CN will be shown to be a result of collisional excitation.

In spite of the low precision of many of the CN results discussed here, there is no question that the dominant mechanism exciting CN is the CBR. Therefore, the results presented here provide the largest body of data to support the homogeneity of the CBR even if it is only on the scale of a few hundred parsecs.

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