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COSMIC BACKGROUND RADIATION TEMPERATURE AT 2.64 MILLIMETERS[1]

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ABSTRACT

A precise value for T_{CBR} at 2.64 mm is reported using interstellar CN molecules in absorption in the direction of ζ Oph. A search for CN emission at 2.64 mm allows us to set a strong limit on local excitation sources that could elevate the population of the 2.64 mm rotational states above that expected from the cosmic background radiation. To one standard deviation, our observations show that $T_{loc} \leq 31$ mK. A reanalysis of data previously reported has improved the precision of the optical equivalent widths so that this source of uncertainty is now 13.3 mK. Uncertainties in the saturation correction model add to the error budget. The final value for $T_{CBR} = 2.796(+0.014, -0.039)$ K.

Subject headings: cosmic background radiation — interstellar: molecules

I. INTRODUCTION

Precise measurements of the spectrum of the cosmic background radiation (CBR) provide information about the statistical history of the universe at redshifts which are not accessible by other means. Deviations of the CBR from a pure blackbody spectrum might be expected from a wide variety of phenomena. Current data at wavelengths beyond the intensity peak ($\lambda \geq 1$ mm) are fully consistent with a blackbody spectrum; a single temperature fits the data at all wavelengths, Johnson and Wilkinson 1987). The situation at shorter wavelengths ($\lambda \leq 1$ mm) is not so clear since CBR data obtained from a recent rocket measurement (Matsumoto *et al.* 1988) has been analyzed to show a departure from a true blackbody spectrum. The rocket data revealed excess radiation of $\sim 10\%$ at $\lambda \leq 1$ mm relative to the spectrum at $\lambda \geq 1$ mm. However, the rocket data may not be consistent with an earlier balloon measurement (Peterson, Richards, and Timusk 1985), although the balloon data were of lower precision. If the Matsumoto results are correct, then a precise measurement of the CBR temperature in the 1–3 mm region could help constrain the interpretation of these results (Smoot *et al.* 1988).

The CN molecule in diffuse interstellar clouds has proven to be a remarkable thermometer for determining T_{CBR} at $\lambda = 2.64$ mm and at $\lambda = 1.32$ mm (Crane *et al.* 1986; Meyer and Jura 1986). This is so since, in the absence of other excitation mechanisms, the populations of the rotationally split ground state of CN are in statistical equilibrium with the CBR radiation. In addition, there are observable optical absorption lines originating from the ground-state rotational levels which, in an optically thin interstellar cloud, can be used to provide an accurate determination of the relative populations of the rotational states, and thus, a measurement of the equilibrium temperature of CN. With no other mechanisms to excite CN, this is the temperature of the CBR.

To determine T_{CBR} with a precision of 1% using CN absorption lines, it is necessary to accurately measure the relative populations of the rotational states, and, in addition, to verify that mechanisms other than the CBR are not important to the required level of precision. In this paper we shall improve the accuracy with which T_{CBR} is known by considering each of these issues. We have reanalyzed our CN absorption line data toward ζ Oph to provide more accurate values for the CN equivalent widths. Also, we have used some new CO data to better understand the velocity structure of the interstellar clouds in an effort to explore possible errors in saturation corrections which are used to relate the observed equivalent widths to the relative rotational state populations. In addition, we have carried out a careful search for CN emission at 2.64 mm to place a strong upper limit on *any* excitation mechanism that would cause CN to be out of statistical equilibrium with the CBR. With these improvements, we are able to determine T_{CBR} to a precision of $\sim 1\%$ where we have included estimates for all reasonable sources of systematic error.

In § II, we present the optical absorption line data and reanalysis, and discuss the saturation corrections in detail. In § III, we present the results of an observational search for CN emission at 2.64 mm and use this data to place limits on any mechanisms other than the CBR which could excite CN molecules. In § IV, we combine the results of §§ II and III to present a new value for T_{CBR}. In § V, we discuss some of the implications of our results.

II. OPTICAL ABSORPTION LINES

The optical data discussed here are the same as those used by Crane *et al.* (1986). These observations were made during two observing runs in 1984 July and 1985 June at the ESO 1.4 m coudè telescope using the echelle spectrograph with

[1] Based on observations obtained at the European Southern Observatory.

a Reticon detector. The observations consisted of individual 20 minute integrations each with a resolution of 150,000 ($2\ \mathrm{km\ s^{-1}}$).

a) *Equivalent Widths*

In the previous analysis of these data (Crane *et al.* 1986), nightly averages and their dispersion were used to determine the CN equivalent widths and errors. This procedure resulted in errors in the equivalent widths which were larger than expected based on the statistical uncertainties in the individual spectra. In the process of measuring the ^{13}CN equivalent width from these same data, Crane and Hegyi (1988) developed an improved analysis technique. This new technique made it possible to identify nonstatistical fluctuation in the data, and hence reduce the uncertainty in the equivalent widths.

The first step in the application of the new analysis technique was to fit each of the 61 individual 20 minute spectra to the combination of a linear continuum plus Gaussian absorption lines. A more complex continuum function was not warranted by the data. This procedure yielded values for the depth and width of the lines, and most important, provided an objective criterion for rejecting spectra which did not have good χ^2. Six of the 61 spectra were rejected by this criterion. For the most part, these spectra had large χ^2 caused by positive spikes in the continuum which we associated with low-level cosmic-ray events in the Reticon detector, but which had not been detected by directly inspecting the spectra.

By combining the results of the fitting procedure for the depth and width of the absorption lines, we obtained values for the equivalent widths of the $R(0)$, $R(1)$, and $P(1)$ lines for each of the 20 minute spectra. Even though the true line profile may not be precisely a Gaussian, this technique gives an unbiased measurement of the equivalent widths as shown by Palazzi, Mandolesi, and Crane (1988). Histograms of the equivalent widths for the $R(0)$ and $P(1)$ lines are shown in Figure 1. In determining the $R(0)$ equivalent width, we allowed for the ^{13}CN line (Crane and Hegyi 1988) so that our ^{12}CN line is free of this source of contamination.

The histograms were fitted to Gaussians to determine the mean and standard deviation of the mean for each of the absorption lines. Fitting Gaussians to histograms raises the question of whether or not the number and size of the bins introduces any error in the determination of the mean and the error in the mean. The values for the equivalent widths reported here have been determined from histograms using from 7 to 25 bins, and the mean values do not fluctuate by more than 10% of their standard deviations. Nevertheless, the quoted errors include an allowance for this source of error.

TABLE 1

CN EQUIVALENTS WIDTHS

Line	Equivalent Width (mÅ)	1986 Result (mÅ)
$R(0)$.........	7.746 ± 0.041	7.646 ± 0.091
$R(1)$.........	2.454 ± 0.021	2.420 ± 0.051
$P(1)$.........	1.255 ± 0.020	1.254 ± 0.067

Table 1 contains the new equivalent widths of the CN $R(0)$, $R(1)$, and $P(1)$ lines, and also contains, for comparison, the equivalent widths from the previous analysis (Crane *et al.* 1986). The main difference between the two data analyses is the substantial reduction in the uncertainties which has been obtained using the new analysis technique. However, the size of the $R(0)$ equivalent width has increased by $\sim 1\ \sigma$. We believe that this is due to the increased sensitivity of the histograming technique to pick out low-level noise or cosmic-rays events.

It is important to realize that the determination of T_{CBR} using CN absorption lines depends on the ratio of the equivalent widths and only depends on the actual equivalent widths as it effects the saturation corrections. For the relatively unsaturated lines studied here, an overall scale error or slight nonlinearity in the detector would have a very small effect. We estimate that errors of this sort would change T_{CBR} by about ± 5 mK. We cannot rule out these errors at this level and make allowance for this uncertainty in the discussion in § IV.

b) *Saturation Corrections*

In determining the actual state populations from the observed equivalent widths, it is necessary to correct for satu-

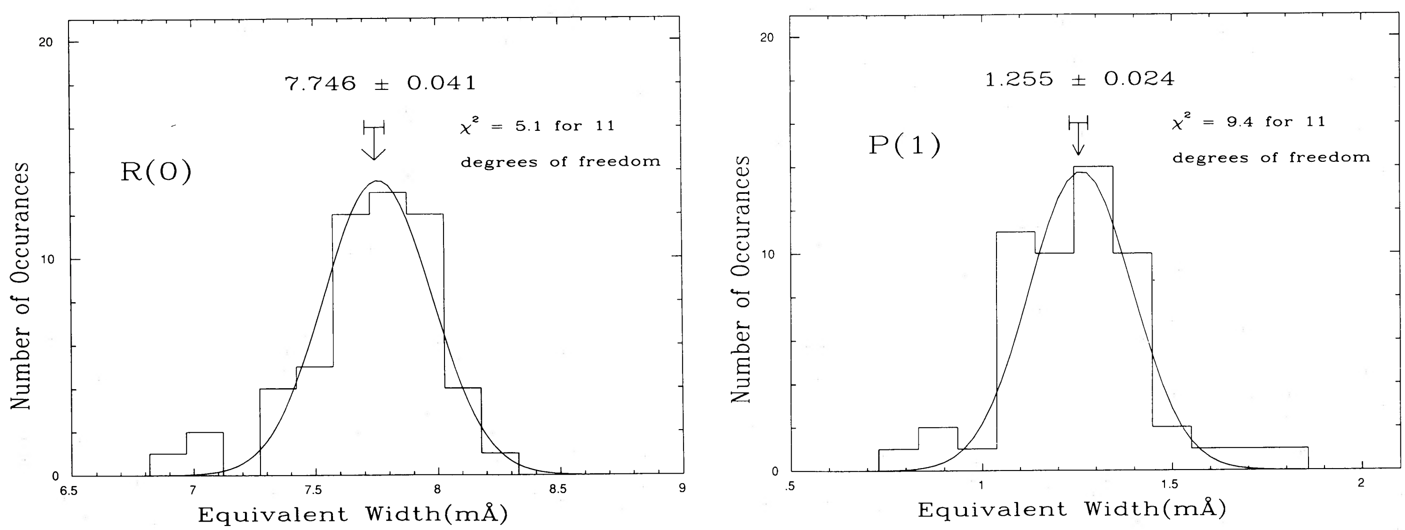

FIG. 1.—Upper section is the histogram of the $R(0)$ equivalent widths. The solid line is a Gaussian that has been fitted to the data to determine the mean and standard deviation of the mean as listed in Table 1. The lower section is the same for the $P(1)$ line.

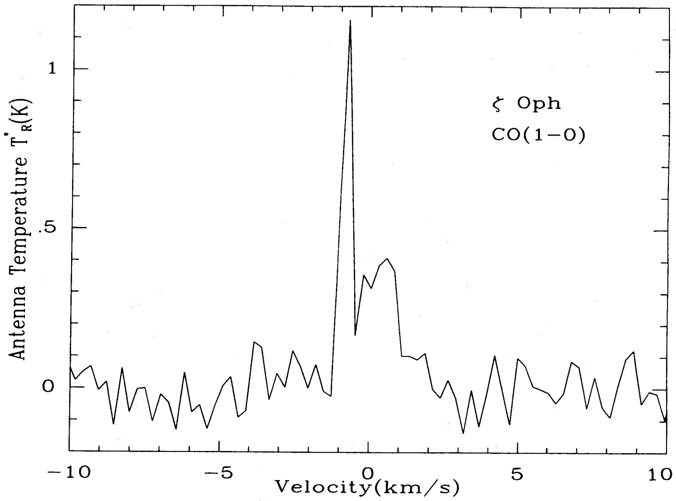

FIG. 2.—CO emission toward ζ Oph velocity is LSR

ration effects. This correction requires an accurate knowledge of the true line profile.

For the CN optical lines toward ζ Oph, it has been traditional to use a single Gaussian line profile for the saturation correction (Hegyi, Traub, and Carleton 1972; Meyer and Jura 1986; Crane *et al.* 1986), and there is some evidence from the agreement of the $P(1)$ and $R(1)$ excitation temperatures that this is correct. However, millimeter observations of CO toward ζ Oph (Langer, Glassgold, and Wilson 1987; Crutcher and Federman 1987) show a multicomponent structure with up to four relatively narrow lines. (See Fig. 2.) Convolving the observed CO lines with the optical resolution yields a profile that is consistent with the observed CN profile (Black and van Dishoeck 1988). This model should also be consistent with the observed optical CH line profiles (Palazzi, Mandolesi, and Crane 1988), but it is not unless ad hoc changes to the relative intensities of the individual cloud components are made.

The optical data described above yielded a determination of the intrinsic width of the CN lines based on the assumption of a single Gaussian line profile as discussed by Crane *et al.* (1986). However, the optical spectral resolution was not sufficient to resolve individual components as narrow as those seen in the CO radio data, if such components are indeed present for CN. Analysis of CH absorption lines at 3878 Å and at 3886 Å show broader widths than the CN lines (Palazzi, Mandolesi, and Crane 1988). This could be due to simple thermal line broadening which would lend support to the single Gaussian component model for both the CN and CH profiles.

Although the CN and CH optical data are fully consistent with a single Gaussian line profile, multicomponent models can be made which are consistent with the data. The simplest model, having n equal components with the relative equivalent widths being $1/n$ of the single component equivalent width and the line widths also being $1/n$ of the single component line width, has no effect on the CN excitation temperature or on T_{CBR}.

In order to estimate the error in T_{CBR} introduced because of our lack of knowledge of the CN line profile, we have studied several multicomponent models. These models met the following criteria: (1) T_{CBR} must be the same for each component of the model; (2) the widths of the components must agree with the CO widths, and (3) the model profiles must be consistent

TABLE 2

CBR TEMPERATURES

Line Ratio	T	T_{exc}
$R(1)/R(0)$	2.9578 ± 0.0162	2.79598 ± 0.0156
$P(1)/R(0)$	2.9944 ± 0.0276	2.79681 ± 0.0251
Average	···	2.7962 ± 0.0133

with the observed optical profiles when convolved with the optical resolution.

If the CN lines are multicomponent, then the most reasonable choice of a model is one in which the relative column densities of the CN components are chosen in proportion to the column densities of the CO(1–0) components along this line of sight (Langer *et al.* 1987). Using this model to calculate the saturation corrections would decrease T_{CBR} by 18 mK, but would also reduce the uncertainty in the local excitation (See the discussion in § IV).

In general, if the CN absorption line consists of narrow components unresolved in the optical data, then the saturation correction will be larger than for the single-component model. With this in mind it is certainly possible to imagine scenarios that are consistent with our requirements and that would have a relatively larger effect on T_{CBR}.

In the following analysis only the single Gaussian line profile with a width of 19.0 mÅ as determined by Crane *et al.* (1986) will be considered. This is the simplest interpretation of our data. The consequences of using a multicomponent model will be discussed in § IV. Table 2 presents the temperatures determined directly from the measured equivalent widths, T, and the saturation corrected excitation temperatures, T_{exc}. The errors in Table 2 are derived from the equivalent widths using standard procedures for the propagation of errors. It may simply be extremely fortuitous that the temperature determined from the $R(1)/R(0)$ line ratio agrees so well with that determined from the $P(1)/R(0)$ ratio. On the other hand, it may indicate that our saturation correction model is the correct one.

III. CN EMISSION AT 2.64 MILLIMETERS

It was realized several years ago that if the rotational states of the CN molecule were not in statistical equilibrium with the CBR, it would be possible to observe CN in emission (Penzias, Jefferts, and Wilson 1972). However, at that time, the optical absorption line measurements were not precise enough to motivate a careful search for CN emission, nor were millimeter detectors sensitive enough to make it possible to carry out a high-precision search for CN emission. That situation has changed. We report here on a careful search for CN emission from the ζ Oph cloud at $\lambda = 2.64$ mm.

a) Observing Details

Observations were made in 1987 May using the NRAO[2] 12 m telescope located on Kitt Peak, Arizona. The half-power beam width (HPBW) was 65″. The forward scattering and spillover efficiency, $\eta_{fss} = 0.80$ (P. Jewell, private communication). The receiver was a dual channel SIS receiver, with a typical single sideband receiver temperature of 100 K in one channel and 140 K in the other. The two receivers detected orthogonal linear polarizations. System temperatures on the sky account-

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

ing for spillover and atmospheric absorption and emission were mostly in the range 400–800 K. Both receiver channels were tuned for single sideband reception, so there is no uncertainty in the sideband gain ratios in the calibration.

Each receiver ouput was fed into a 128 channel filter bank providing a spectral resolution of 100 kHz (0.26 km s^{-1}). The expected line width was ~ 1.0 km s^{-1}, based on observations of the CO($J = 1$–0) line, and based on the optical CN absorption lines discussed above. The receiver was tuned to center the frequency of the strongest hyperfine component $(K, J, F) = (1, 3/2, 5/2) \rightarrow (0, 1/2, 3/2)$ at a rest frequency of 113,491.15 GHz. With our bandwidth, we could also detect the $F = 3/2 \rightarrow 1/2$ component at 113,488.39 GHz. Theoretically, this component is down by a factor 2.7 in relative intensity from the strongest line. (This means that the contribution to the overall signal to noise by this component is $(1/2.7)^2$, and we have not considered it further.)

The position observed was $\alpha(1950) = 16^h34^m24^s.2$, $\delta(1950) = -10°28'02''$. The observations were taken in a position switching mode with alternating 15 s observations on the source and the reference position. Position switching was employed since, at the time of our observations, the receiver was not capable of frequency switching. These observations were combined into 6 minute scans. The reference position was 30'E and 30'N (in α and δ) of the source position. The reference position was checked for CO emission by reference to a position again 30'N and 30'E of the primary reference position. No line was detected with an rms noise level in T_R^* of 66 mK. Since the CO line in the direction of ζ Oph has a peak intensity of 1.5 K, this means that the CO line falls by at least a factor of 22 from ζ Oph to the reference position. If the CN falls by the same factor, although it would be likely to fall by even more since it is harder to excite than CO, low-level CN emission in the off position could reduce the observed CN line strength by, at most, 4%.

The total CN observing time on source was 30 hr. Periodic pointing checks were made by observing various planets. Half the observations were taken with the receiver retuned to shift the spectrum by five channels. This was done to reduce our sensitivity to possible low-level artifacts in the filter banks.

Intensity calibrations were carried out by alternately comparing the sky to an ambient temperature reference. Scale factors that were used incorporated a two-layer atmospheric model (Kutner 1978), with atmospheric opacities determined from periodic antenna tippings. Atmospheric opacities ranged from 0.13 to 0.20. All intensities are expressed as T_R*, which is the source antenna temperature corrected for atmospheric, ohmic, and all spillover losses (Kutner and Ulich 1981). It will be argued later that the source probably fills the main beam, so we can take the source coupling efficiency to be approximately unity, meaning that T_R* is close to the source radiation temperature.

In the data reduction process, each 6 minute scan was inspected (with the data from each polarization being treated as a separate scan). Baselines were removed from each scan. Approximately two-thirds of the data were well fitted by linear polynomials, with the remaining third being divided equally between second- and third-order baselines. Scans for which the magnitude of the baseline curvature significantly exceeded the rms noise level were not included in the final analysis. In the inspection of individual scans, occasional bad channels were removed by assigning a value equal to the average of the values of the channels on either side of the bad channel. Scans with bad channels near the expected CN line positions were discarded. All scans were then averaged, being weighted inversely as the square of the rms noise level in the scan.

b) *Millimeter Results*

The CO spectrum in the direction of ζ Oph is shown in Figure 2. There are at least two velocity components present: one at +0.3 km s^{-1}, and the other at −0.7 km s^{-1}. (All velocities are with respect to the local standard of rest, LSR). Each component is ~ 0.5 km s^{-1} wide. Our results are in basic agreement with the spectrum published by Langer *et al.* (1987). We use our own CO spectrum as a template in searching for possible CN emission, since our CO spectrum duplicates our beam size and other observational parameters. As mentioned above, a model of the optical absorption lines based on the CO lines could reproduce the observed CN lines (Black and van Dishoeck 1988).

The CN millimeter spectrum is shown in Figure 3. No line is detected with an rms noise level of 6.9 mK.

c) *Millimeter Analysis*

We would like to relate the observed upper limit on T_R*, the excess radiation temperature due to collisional excitation of CN, to T_{loc}, the excess excitation temperature due to collisions or other local excitation mechanisms. We define T_{loc} such that:

$$T_x = T_{CBR} + T_{loc} ,$$

where T_{CBR} is the true cosmic background radiation temperature, and T_x is the actual excitation temperature of the observed transitions, measured from the optical data to be 2.796 K. Note that from this definition, $T_{loc} \geq 0.0$. These quantities are related to the observed radiation temperature by the equation

$$T_R{}^* = \eta_c T_0 \left[\frac{1}{\exp(T_0/T_x) - 1} - \frac{1}{\exp(T_0/T_{CBR}) - 1}\right](1 - e^{-\tau}) ,$$

where $T_0 = h\nu/k = 5.444$ K and τ is the line optical depth. For $T_{loc} \ll T_{CBR}$, this reduces to

$$T_R{}^* \cong (0.74)\eta_c T_{loc}(1 - e^{-\tau}) . \quad (1)$$

Note the factor 0.74 would be 1.0 in the Rayleigh-Jeans part of the spectrum.

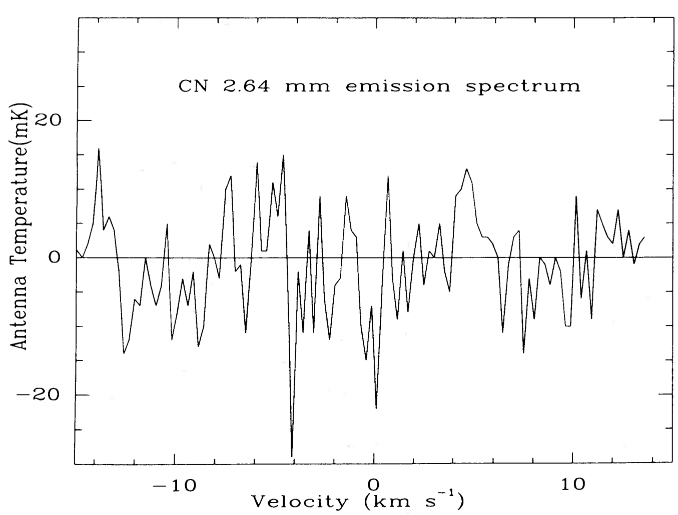

FIG. 3.—Spectrum of CN emission toward ζ Oph velocity is LSR. Any CN emission would be expected at velocities between −0.7 km s^{-1} and 0.3 km s^{-1}.

The optical depth can be determined from N_1 and N_0, the column densities in the two rotational states. These are directly determined from the optical absorption lines. Equivalently, we can use N_1 and T_x, giving

$$\tau = \left(\frac{A_{10} c^3 N_1}{8\pi v^3 \Delta v}\right)(e^{T_0/T_x} - 1) , \qquad (2)$$

where A_{10} is the spontaneous decay rate, and Δv is the line-width in velocity units. We take $A_{10} = 1.193 \times 10^{-5}$ s^{-1}, $N_1 = 9.424 \times 10^{11}$ cm^{-2}, $\Delta v = 1.47 \times 10^5$ cm s^{-1}, and $T_x = 2.796$ K. In addition, only one third of the total intensity is in the strongest hyperfine component, giving $\tau = 0.113$.

The source coupling efficiency, η_c, is given by (Kutner and Ulich 1981)

$$\eta_c = \iint_{\Omega_s} P_n(\Omega) B_n(\Omega) d\Omega \Big/ \iint_{\Omega_d} P(\Omega) d\Omega ,$$

where P_n is the normalized antenna power pattern, B_n is the normalized source distribution, Ω_s is the source solid angle, and Ω_d is the solid angle covered by the main beam and near sidelobes. For a source that uniformly fills the main beam and the near sidelobes, $\eta_c = 1$.

The observations of Langer *et al.* 1987 provide a low spatial resolution map of CO toward ζ Oph. This provides good evidence that the cloud not only fills the antenna beam, but fills it uniformly and therefore that $\eta_c = 1$.

To obtain an upper limit to T_{loc}, we must use our data to assign a meaningful upper limit to T_R*. The rms of 6.9 mK is per channel, but the line is broader than a single channel, so there is additional information in channels away from the line center. We can use our observations of CO in the direction of ζ Oph to define a line profile function $\phi(v)$, which can take on values between 0 and 1. In this cloud, the CO line is likely to be optically thin based on our upper limit for the ^{13}CO line as well as on the observations of Langer, Glassgold, and Wilson (1987). If T_R* is the peak line temperature, then the temperature in channel j is given by

$$T_j = T_R{}^* \phi_j(v) .$$

Each channel provides a measure of T_R*, given by

$$T_R{}^* = \left(\frac{T_j}{\phi_j}\right) \pm \left(\frac{\sigma}{\phi_j}\right) ,$$

where σ is the rms noise level per channel, and ϕ_j is the average value of $\phi(v)$ in channel j. We then take a weighted average of the various values of T_R*, with the weights being $\phi_j{}^2$. This gives a final uncertainty in T_R* of $\sigma/(\Sigma\phi_j{}^2)^{1/2}$. From our data, this gives

$$T_R{}^* = -9.5 \pm 5.2 \text{ mK} .$$

It must be remembered that T_{loc} was defined to be positive or zero, meaning that T_R* must also be positive or zero. A formal negative value for T_R*, as opposed to a zero or positive value, for instance, implies that it is less likely that the true value of T_R* is positive. We discuss the interpretation of this result in terms of an upper limit to T_{loc} below. We note that our limit on T_R* may be used to constrain models of the ζ Oph cloud (van Dishoeck and Black 1986).

d) Limit on T_{loc}

Using the result for T_R* and substituting in equation (1) above, we find the formal result that the excess radiation temperature due to collisional excitation within the CN interstellar cloud is

$$T_{loc} = -120 \pm 66 \text{ mK} .$$

Since there is no known process which can selectively depopulate the upper level rotational states of CN (i.e., cool the molecule below T_{CBR}), T_{loc} must be nonnegative. Consequently, one way of specifying the constraint which our measurement imposes on T_{loc} taking into account that T_{loc} must be nonnegative is to state the probability that $T_{loc} \geq 0$ as deduced from our measurements. Based on the observed distribution of values of T_R* obtained from each 6 minute scan which we find to be Gaussian, the probability that $T_{loc} \geq 0$ is the same as the fractional area under a Gaussian which lies beyond $+(120/66)\ \sigma = 1.82\ \sigma$. Thus, there is less than a 4% chance that $T_{loc} \geq 0$ based on our measurements. Consequently, to 1 σ, we need not include the uncertainty in T_{loc} in our error analysis.

While the above discussion is correct statistically, we recognize that we were "lucky" in that our measured mean value for T_{loc} is almost 2 σ below zero so that we could quote a stronger limit on T_{loc} than could be expected given the precision of our measurement. If the true value of T_{loc} were zero and we repeated our measurement many times obtaining the same measuring precision as for our present measurement, our measured mean value for T_{loc} would be zero and the error for a single measurement would be the same as our quoted error, 66 mK. We prefer to quote our errors using this more conservative expectation. Consequently, for a Gaussian distribution of measured values centered on $T_{loc} = 0$, one finds that 68% of the area under the curve lies below $+0.47\ \sigma$ so we take 0.47×66 mK = 31 mK to be our 1 σ upper limit on T_{loc}.

Summarizing the conclusions of our measurement on local sources of excitation which could contribute to our measured value of the excitation temperature of the 2.64 mm transition of CN, we find

$$T_{loc} = 0.000(+0.031 - 0.000) \text{ K} .$$

IV. T_{CBR} AT 2.64 MILLIMETERS

Since no local excitation of the CN molecules has been found, the CBR temperature is the observed CN excitation temperature. Therefore, the main topic of this section is the errors which can be assigned to the value of T_{CBR}.

There are four sources of error that need to be considered. These are (1) statistical error (± 13.3 mK) in the equivalent widths; (2) uncertainty in the equivalent widths (± 5 mK) due to a scale error or nonlinearity in the detector; (3) error in the local excitation of CN(-31 mK); and (4) error introduced by uncertainty in the model for the saturation correction (-18 mK). The first two sources of error can be added in quadrature. The second two are asymmetrical and should be added to the negative side of the error, but not on the positive side. Adding the latter two in quadrature with the first two yields:

$$T_{CBR} = 2.796(+0.014;\ -0.039) \text{ K} .$$

The uncertainty in the saturation correction that has been included is our best guess based on a reasonable physical model. This may in fact over estimate the total error in the final result for the following reason. If the CN lines consist of several intrinsically narrow components, then in calculating both the saturation correction and the optical depth in equation (2), the true narrow width should be used. The radio optical depth τ will increase resulting in a decrease in the error estimate for T_{loc}. On the other hand, the saturation correction will increase, resulting in a lower value for T_{CBR}. For example, a model based strictly on the CO line strengths and using a CN line-width of 0.50 km s^{-1} would yield $T_{CBR} = 2.778 \pm 0.028$. This value lies well within the error limits above.

We have not included estimates of possible systematic effects which we are not aware of or for which we have no evidence such as nonlinearities in the detector or in the analysis procedures.

V. DISCUSSION

The value for T_{CBR} presented here is the second most accurate measurement at wavelengths longer than 2 mm after the measurement of Johnson and Wilkinson (1986). The Johnson and Wilkinson value of $T_{CBR} = 2.783 \pm 0.025$ K was measured at 1.2 cm using a balloon-borne radiometer. It agrees very well with our value of $T_{CBR} = 2.796^{+0.014}_{-0.041}$. Both values are higher than previously reported ground-based measurements but agree with each other. This result also agree well with the value of $T_{CBR} = 2.799 \pm 0.018$ at 1.16 mm given by Matsumoto *et al.* (1988).

The value of T_{CBR} reported here does not include a correction for local excitation of CN in the interstellar cloud toward ζ Oph. The millimeter wave observations reported here show that it is extremely unlikely that CN is excited above the CBR temperature by any process. Previously, a theoretical estimate of the electron collisional excitation cross-section (Thaddeus 1972) and an observational estimate (Meyer and Jura 1985) of the electron density had been used to correct the observed CN excitation temperature.

In deriving the value of T_{CBR} reported here, we have tried to take the most conservative point of view in assessing the sources of error. This is particularly true with regard to the saturation correction and the possible source of local excitation.

The observations of Meyer and Jura (1986) of the CN absorption lines toward ζ Oph yielded a value of $T_{CBR} = 2.663 \pm 0.059$ K. However, this included a correction of -0.06 ± 0.04 K for local excitation of CN by electrons. Using the local excitation correction determined here would give a value of $T_{CBR} = 2.723(+0.044;\ -0.054)$, which is consistent with our value. However, Meyer and Jura used a different b value than used here to determine the saturation correction. Had they used the same b value for the saturation correction, their value would be lower by ~50 mK and our measurements would disagree at the 2 σ level. We do not understand the origin of this disagreement, but note that unaccounted for systematic errors might be expected to be larger in the data of Meyer and Jura since they had longer integration times and lower spectral resolution than our data.

Table 3 contains a summary of the most recent observational results on the CBR spectrum. In compiling Table 3, we have corrected the results of Meyer and Jura for ζ Oph at 2.64 mm to account for the corrections mentioned above. There is no net change from the value given in their paper, but this is fortuitous.

In order to test the assumption that the CBR is a pure blackbody spectrum at wavelengths longer that 1 mm we take the weighted average of the values in Table 3 for $\lambda \geq 0.1$ mm. This yields a value of $T_{CBR} = 2.771 \pm 0.012$ K with a $\chi^2 = 29$ for 18 degrees of freedom. The data point of Kogut *et al.* 1988 at 3.0 cm is the most discrepant and removing that point from the weighted average yields $T_{CBR} = 2.777 \pm 0.012$ with a $\chi^2 = 22$ for 17 degrees of freedom. This substantial reduction in the χ^2 suggests it would be useful to remeasure the value of Kogut *et al.* In fact, the Kogut *et al.* point has been criticized as being too low due to sidelobe contamination in the Earth atmospheric correction (R. B. Partridge, private communication). Thus, there is good evidence that the spectrum of the CBR is that of a blackbody to high accuracy at wavelengths longer than 1 mm.

Measurements at wavelengths shorter than 1 mm in Table 3 come from the rocket experiment of Matsumoto *et al.* (1988) and clearly indicate a departure from a pure blackbody spectrum. Several explanations for this departure have been suggested (Hayakawa *et al.* 1987; Smoot *et al.* 1987; Daly 1988). For example, an explanation in terms of Comptonization by known relativistic electrons would require a Comptonization parameter, y, as large as 0.028, and a value of $T_{CBR} = 2.60 \pm 0.04$ at long wavelengths (Hayakawa *et al.* 1987). This value for T_{CBR} is ruled out by more than 3 σ by the two most precise observational results at 1.2 cm (Johnson and Wilkinson 1986) and our present value at 2.64 mm.

However, due to the important cosmological implications of the Matsumoto *et al.* results, it is imperative that they be confirmed. If they are confirmed, then the CN results presented here will serve as a strong constraint on the models that could provide explanations for the distortion of the CBR spectrum from that of a pure blackbody.

TABLE 3

RECENT MEASUREMENTS

Wavelength (cm)	T_{CBR} (K)	Reference
50.0	2.45 ± 0.70	1
21.2	2.28 ± 0.39	2
12.0	2.79 ± 0.15	3
8.1	2.58 ± 0.13	4
6.3	2.70 ± 0.07	5
3.0	2.61 ± 0.06	6
0.909	2.81 ± 0.12	7
0.333	2.60 ± 0.10	8
1.2	2.783 ± 0.025	9
0.264	$2.796^{+0.014}_{-0.039}$	10
0.132	$2.75^{+0.24}_{-0.29}$	11
0.264	2.70 ± 0.04	12
0.132	2.76 ± 0.20	...
0.116	2.799 ± 0.018	13
0.071	2.963 ± 0.017	...
0.048	3.150 ± 0.026	...
0.351	2.80 ± 0.16	14
0.198	$2.95^{+0.11}_{-0.12}$	14
0.148	2.92 ± 0.10	14
0.114	$2.65^{+0.09}_{-0.10}$	14
0.100	$2.55^{+0.14}_{-0.18}$	14

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