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COSMIC BACKGROUND RADIATION TEMPERATURE FROM CN ABSORPTION

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ABSTRACT

Precise high-resolution measurements of the interstellar lines of CN near 3874 Å toward the star ζ Oph provide a new measurement of the cosmic background radiation temperature of 2.74 ± 0.05 K at 2.64 mm and of 2.75 (+0.24, −0.29) K at 1.32 mm. Using a spectral resolution of 156,000, the intrinsic width of these lines is found to be 19.0 ± 0.5 mÅ, which is substantially smaller than previously reported and requires larger saturation corrections than used in previous work to determine the CN excitation temperature.

Subject headings: cosmic background radiation — cosmology — interstellar: molecules — line profiles

I. INTRODUCTION

Measurements of the absorption-line spectra of the interstellar lines of CN contained the first direct evidence for the cosmic background radiation (CBR) (McKellar 1940). Unfortunately these were not recognized as such until after the "discovery" of the cosmic background radiation by Penzias and Wilson (1965) and its interpretation by Dicke *et al.* (1965). Subsequently several observers have determined the cosmic background radiation temperature from the CN absorption lines. These have been reviewed by Thaddeus (1972) and more recently by Meyer and Jura (1985). It now appears possible that the CN lines may provide the most precise measurement of the CBR temperature at the wavelengths sampled by CN since the systematic effects associated with these observations are becoming better understood and the random and calibration errors appear to be smaller than for the current microwave measurements.

The CN absorption spectrum samples the CBR at wavelengths of 2.64 mm and 1.32 mm. These two points lie fortuitously close but on different sides of the peak of a 2.7 K blackbody spectrum and are, therefore, very good measures of the Planckian nature of the radiation spectrum. However, the line sensitive to the radiation at 1.32 mm is extremely weak and has so far not been observed with adequate precision to contribute substantially to the question of possible deviations from a pure Planckian spectrum. Future observations could improve this situation.

The CN absorption-line measurement technique for determining the CBR temperature is independent of the ground-based microwave radiometer measurements (Smoot *et al.* 1985) and of the balloon-borne bolometer measurements (Peterson, Richards, and Timusk 1985). Thus the CN results provide an independent test as well as a confirmation of these other techniques.

Recently Meyer and Jura (1984, 1985) have reported new observations of CN absorption-line spectra in the direction of the stars ζ Oph, ζ Per, and *o* Per. They report a value for the CBR temperature of 2.70 ± 0.04 K at 2.64 mm and of 2.76 ± 0.20 K at 1.32 mm. Meyer and Jura discuss the CN level structure and its relation to the CBR temperature which will not be repeated here.

We have reobserved the CN absorption spectrum in the star ζ Oph and report substantial agreement with the results of Meyer and Jura, although we do not agree in detail with their results. We have obtained precise values of the $R(0)$, $R(1)$, and $P(1)$ equivalent widths. In addition, we present a detection of the $R(2)$ line of CN at 3873.369 Å which is uncontaminated by telluric lines. It is this line which is sensitive to the cosmic background radiation at 1.32 mm. Our data reveal a substantially narrower intrinsic line width for the CN lines than reported by Hegyi, Traub, and Carleton (1972). Consequently, it is necessary to use larger curve of growth corrections to the observed equivalent widths than was used in previous analyses. We also report the variability of a telluric line at 3873.167 Å which may cast some doubt on the quantitative interpretation of a previous detection of $R(2)$ in ζ Oph (Meyer and Jura 1984).

II. OBSERVATIONS AND DATA REDUCTION

The data described here were obtained at the 1.4 m coudé auxilliary telescope of the European Southern Observatory on La Silla. The coudé echelle spectrograph with a Reticon detector was used during 12 nights beginning on 1984 July 30 and again during 10 nights beginning on 1985 July 15. Unfortunately, because of severe weather conditions, only nine of the nights yielded any data at all, and of these only seven nights yielded data of sufficiently high quality to be useful for this program.

For the 1984 observations, the spectrograph was set up to produce a resolution of 156,000 at 3875 Å. Individual diodes of the Reticon sampled 17.4 mÅ of the spectrum resulting in minimal oversampling. In 1985, the slit was opened slightly relative to the 1984 setting, resulting in resolutions of 116,000 and 100,000. Also in the 1985 observations, the central wavelength was varied over a range of ±0.5 Å from night to night.

Both of these changes were made in an attempt to minimize the effects of coherent noise arising from the Reticon. Figure 1 is an example of the high-quality data we have obtained.

The observing procedure was to fix the spectrograph setting for each night, and to divide the observations into relatively short runs of 20–30 minutes. The duration of the individual runs was chosen to be long enough so that photon noise would dominate detector readout noise, and yet short enough to avoid too many nonstochastic "cosmic-ray" events which could render an individual run useless. These latter events, which we tentatively associated with cosmic rays, dominated dark current measurements longer than 20 minutes and were less important in runs with high signal. The thermally generated dark current in a 20 minute run was not significant, and dark current corrections were not necessary.

The gross instrumental signature in the data was removed by subtracting the zero signal output of the individual diodes and dividing by the individual diode sensitivity determined from a spectrum taken with a tungsten lamp. The resulting spectra showed a pronounced repeating pattern noise associated with the Reticon detector. Several methods were used to remove the dominant 4 pixel component of this coherent noise source. The most effective method was a Fourier notch filter which reduced the coherent noise without reducing the resolution.

The coherent noise in the data was the dominant source of uncertainty in the results presented here. Our success using various techniques for removing this noise determined the final signal-to-noise ratio attainable. Changing the central wavelength of the spectrometer from night to night during the 1985 observing season moved the stellar spectrum relative to the pixel positions and helped in reducing the coherent noise in the spectrum averaged over several nights. Observations of a "reference" object at about the same signal level also provided a means of reducing the coherent noise by comparing the ζ Oph spectrum with the reference star in the pixel region where the CN lines occur. Although this noise source limits the precision of our detection of the $R(2)$ line, it does not effect our results for the other lines.

We have also checked for scattered and parasitic light in the instrument by observing the solar spectrum and have verified that such effects are not effecting our results.

III. ANALYSIS AND RESULTS

In this section, we present a determination of the intrinsic line width of the CN absorption lines, measurements of the equivalent widths of the $R(0)$, $R(1)$, $R(2)$, and $P(1)$ lines from which we deduce the temperature of the CBR at 2.64 mm and 1.32 mm, and a discussion of the variability of a telluric line at 3873.167 Å.

a) The Intrinsic Line Width of CN

The data obtained in 1984 had a resolution of 156,000 and were suitable for determining the intrinsic line width of the CN lines. Gaussian line profiles were fitted to the $R(0)$ line data and to the unresolved thorium comparison lines, and line widths (FWHM) of 31.8 ± 0.3 mÅ and 25.8 ± 0.2 mÅ, respectively, were found, indicating that the data had sufficient resolution to determine the intrinsic width of the CN lines. We then determined the instrumental width to be 24.8 ± 0.4 mÅ by assuming the measured thorium line width is the quadratic sum of the true instrumental width and an intrinsic thorium line width of

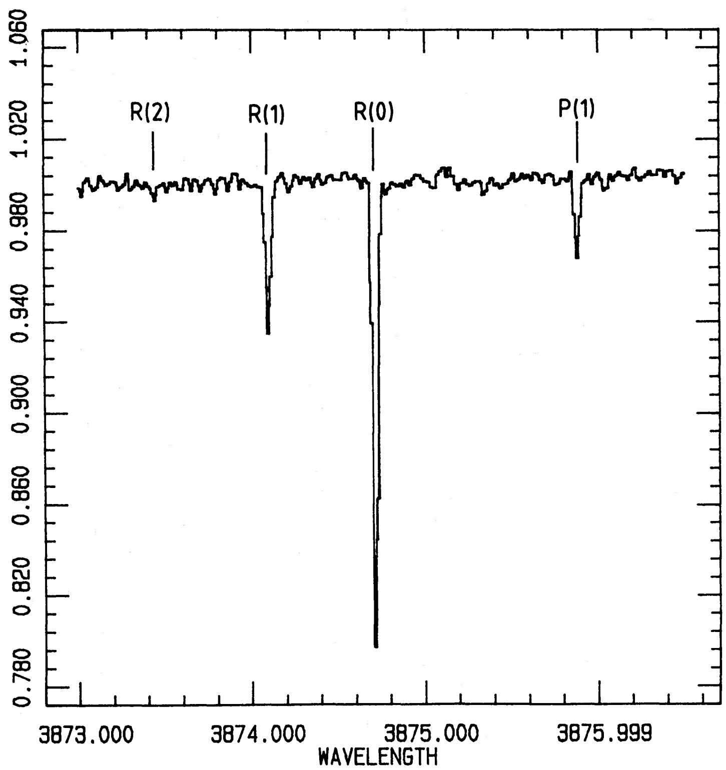

FIG. 1.—Spectrum of the CN lines of ζ Oph at 3874 Å obtained on 1985 July 19. Depth and narrowness of the lines indicates the quality of the ESO spectrograph. Wavelengths of lines are observed wavelengths and not rest wavelengths.

7 mÅ (Palmer 1986). It was then assumed that the intrinsic profile of the CN lines was of the following form:

$$I(x; b, \tau) = \exp\{-\tau \exp[-(x/b)^2]\} ,$$

where τ is the optical depth and the quantity $2[\ln(2)]^{1/2}b$ is the full width at half-maximum of the Gaussian velocity profile. It was also assumed that the instrumental profile was Gaussian, which was a very good approximation as we have verified by checking the profile of a laser line at 6328 Å. The assumed CN profile was then convolved with a Gaussian of width 24.8 mÅ and was fitted to the $R(0)$ line data. The resulting intrinsic CN line width (FWHM) was 19.0 ± 0.5 mÅ, and the optical depth was 0.434 ± 0.010. This implies a velocity spread in the cloud of 0.88 ± 0.02 km s^{-1}, in good agreement with the value of 0.85 km s^{-1} derived by Herbig (1968) for CH^+ in the same cloud. We note that the same analysis for the $R(1)$ line yields a line width of 19.5 ± 1.2 mÅ and an optical depth of 0.117 ± 0.006.

The CN line width determined here assumes that the interstellar cloud contains a single component with a Gaussian velocity spread. This is most likely not strictly true, and hence our line width result is subject to an unknown but presumably small systematic uncertainty. The error we quote is mainly associated with the statistical measuring uncertainties, and takes account of the systematic uncertainties which we know how to estimate, but does not include any estimate of the systematic uncertainties associated with non-Gaussian multicomponent clouds.

Our value for the intrinsic line width of 19.0 mÅ should be compared to the value of 28 mÅ for the same line width reported by Hegyi, Traub, and Carleton (1972). We believe the value derived from our observations is to be preferred for the following two reasons. First, our value is derived from a measured line width of 31.8 mÅ which is already narrower than that of 37 mÅ reported by Hegyi *et al.* (1972) in spite of the fact that our instrumental line width of 24.8 mÅ is broader than the 22 mÅ of Hegyi *et al.* (1972). Second, the CN excitation temperatures derived from the ratios of equivalent widths for the $R(1)$ and $P(1)$ lines to the equivalent width for the $R(0)$ line agree well with each other when using a line width of 19.0 mÅ for the curve of growth correction. This should be the case, of course, since the $R(1)$ and $P(1)$ lines originate from the same level. This point is discussed further below. To place in perspective the difference between an intrinsic line width of 28 mÅ and one of 19 mÅ, we note that the CBR temperature at 2.64 mm is reduced by 0.05 K using a line width of 19 mÅ as compared to the 28 mÅ value.

b) $R(0)$, $R(1)$, *and* $P(1)$ *Equivalent Widths*

In this section, we present equivalent width measurements for the $R(0)$, $R(1)$, and $P(1)$ lines and derive a value for the CBR temperature at 2.64 mm including a discussion of the correction for saturation effects and local electron excitation.

TABLE 1

MEASURED CN EQUIVALENT WIDTHS (mÅ)

Date	$R(0)$	$R(1)$	$P(1)$	$R(2)$
1984 Aug 5	7.665	2.392	1.260	...
1984 Aug 6	7.697	2.499	1.266	...
1984 Aug 8	7.548	2.357	1.138	...
1985 Jul 15	7.604	2.398	1.336	0.053
1985 Jul 18	7.753	2.476	1.306	...
1985 Jul 19	7.512	2.385	1.198	0.090
1985 Jul 22	7.733	2.432	1.273	...
Average	7.646 ±0.091	2.420 ±0.051	1.254 ±0.067	0.072 ±0.026

The equivalent widths of these lines were determined by two different techniques in order to check for possible systematic errors in the analysis procedures. First, the intensity in each line relative to the continuum was integrated with respect to wavelength and was compared to the continuum in the usual manner. Second, the lines were fitted to Gaussian profiles and a sloping continuum. The derived parameters for the Gaussians were then used to determine the equivalent widths. Both methods yielded similar values. Table 1 is a summary of our measured CN equivalent widths. The errors quoted in Table 1 are the standard deviations of the individual values around their mean. We believe this is the most conservative approach to estimate the uncertainties in these values since the statistical uncertainties in the individual nightly equivalent widths were only slightly larger than the quoted final error.

We have carefully considered possible sources of systematic error in these data and have not found any significant ones. For example, possible errors due to placement of the continuum when measuring the equivalent widths are less than ±0.02 mÅ. The excellent agreement between the data obtained in 1984 and in 1985 also indicates that if there are any small errors in the instrument behavior they are very constant over at least 1 yr. We checked the system linearity by searching for variations on the equivalent width of the $R(0)$ line as a function of the continuum level in individual runs, but found no significant effect.

In Table 2 we compare the various published equivalent widths for these lines, as well as for the $R(2)$ line discussed below. The data of Thaddeus (1972) are based on a photographic technique that is most likely subject to unknown systematic errors as discussed by Meyer and Jura (1985). Therefore, the discrepancy of our data with Thaddeus is not a serious deficiency. Our results agree well for the $R(0)$ line with those of Hegyi, Traub, and Carelton (1972, 1974), and reasonably well for the $R(1)$ line. This is important because the Fabry-Perot technique of Hegyi *et al.* (1972, 1974) is considerably different than ours. The data of Federman, Danks, and Lambert (1985) were obtained with the same instrument and detector as ours, but under considerably different conditions and agree with our results but are of lower precision than ours.

TABLE 2

COMPARISON OF CN MEASUREMENTS

Source	$R(0)$	$R(1)$	$P(1)$	$R(2)$
Thaddeus	8.27(0.10)	2.78(0.10)	1.40(0.10)	<0.17
Hegyi *et al.* 1972 ...	7.59(0.35)	2.19(0.19)	...	0.077(0.055)
Federman *et al.*	7.50(0.3)	2.50	1.20	...
Meyer and Jura	7.34(0.10)	2.13(0.06)	1.08(0.07)	0.060(0.030)
This paper	7.646(0.091)	2.420(0.051)	1.254(0.067)	0.072(0.026)

The significant difference between our measurements and those of Meyer and Jura (1985) for the equivalent widths of the $R(0)$, $R(1)$, and $P(1)$ lines is a cause for concern, and is the major reason why we delayed publishing our data until we had the second set of observations in 1985. Our equivalent widths are systematically larger than those of Meyer and Jura (1985). We have sought very hard to find possible effects which might give rise to a systematic increase in our equivalent widths compared to those of Meyer and Jura. However, most of these effects would tend to make spectra of lower resolution yield lower equivalent widths. In comparing with the results of Meyer and Jura, we find a marginally significant trend in that the fractional difference between our results and theirs decreases with increasing equivalent width. Since the data of Meyer and Jura were obtained through much larger air masses (~ 5 times) and with lower resolution (~ 3 times), our results should be less sensitive to systematic errors such as weak telluric lines. In summary, we do not understand the differences between our two data sets.

The measured equivalent widths must be corrected for saturation effects before they can be used to determine the CN excitation temperature. The resulting CN excitation temperatures only represent the CBR temperature if there are no other sources of excitation of the CN levels. In Table 3, the uncorrected CN excitation temperatures, T, derived directly from the observed equivalent widths are given. The errors are derived by recomputing this temperature using the one standard deviation limits on the measured equivalent widths found in Table 1. The CN excitation temperatures corrected for curve of growth effects, T_{corr}, are given in the next column where the numbers in parentheses are the uncertainty associated with the curve of growth corrections. These corrections followed the same procedure as described by Meyer and Jura (1985), except that we used an intrinsic line width of 19.0 mÅ to determine the magnitude of the correction. There is excellent agreement between the CN excitation temperature derived from the $R(1)/R(0)$ ratio and that derived from the $P(1)/R(0)$ ratio. This would not have been the case had we used 28 mÅ for the intrinsic line widths of the CN lines in our curve of growth analysis. Since the $R(1)$ and $P(1)$ transitions arise from the same molecular ground state, they are expected to give the same CN excitation temperature. This is further confirmation of our curve of growth corrections.

The weighted average of the two CN excitation temperatures is 2.800 ± 0.027(0.003) K. The uncertainty of ±0.027 is the measurement uncertainty, whereas the ±0.003 is the uncertainty associated with the curve of growth corrections. This latter is a systematic error and should be treated separately from the random measuring errors.

The final value of the CBR temperature at 2.64 mm is obtained by correcting the CN excitation temperature for local excitation due to electrons. To determine this correction, we again adopt the procedure described in detail by Meyer and Jura (1985), and in this case we also adopt their value of $T_{\text{elec}} = -0.06 \pm 0.04$ K. Thus our value of the CBR temperature at 2.64 mm is $T_{\text{CBR}} = 2.74 \pm 0.05$ K, where the error is found by adding the three errors in quadrature. The dominant contribution to the error is the correction for local electron excitation of the CN molecules.

TABLE 3

CBR TEMPERATURE AT 2.64 MILLIMETERS

Line Ratio	T	T_{corr}
$R(1)/R(0)$	2.956 ± 0.031	2.797 ± 0.029(0.003)
$P(1)/R(0)$	3.015 ± 0.071	2.818 ± 0.066(0.003)
Average...........	...	2.800 ± 0.027(0.003)
T_{elec}	...	−0.06 ± 0.04
T_{CBR}	...	2.74 ± 0.05

TABLE 4

CBR TEMPERATURES FROM MEYER AND JURA'S DATA

	CN LINE WIDTH	
SOURCE	28 mÅ	19 mÅ
ζ Oph	2.66 ± 0.06	2.61 ± 0.05
Meyer and Jura	2.70 ± 0.04	2.68 ± 0.04

We have recomputed the CBR temperature using the equivalent widths measured by Meyer and Jura (1985), using the new saturation correction obtained for a line width of 19.0 mÅ, and including the −0.06 K correction for electron excitation. These results are presented in Table 4 and may be compared to the original Meyer and Jura results which used 28 mÅ for the CN line width. The second row of Table 4 recomputes the Meyer and Jura CBR temperature using the results for all three stars they observed. This average result is lower by about one standard deviation than the average of Smoot *et al.* (1985), while the ζ Oph result is about two standard deviations lower.

c) *Detection of the R(2) Line*

The $R(2)$ line was only visible in the spectra with the highest signal to noise and, hence, was only detectable on two of the many nights we observed. Figure 2 shows a plot of the data for

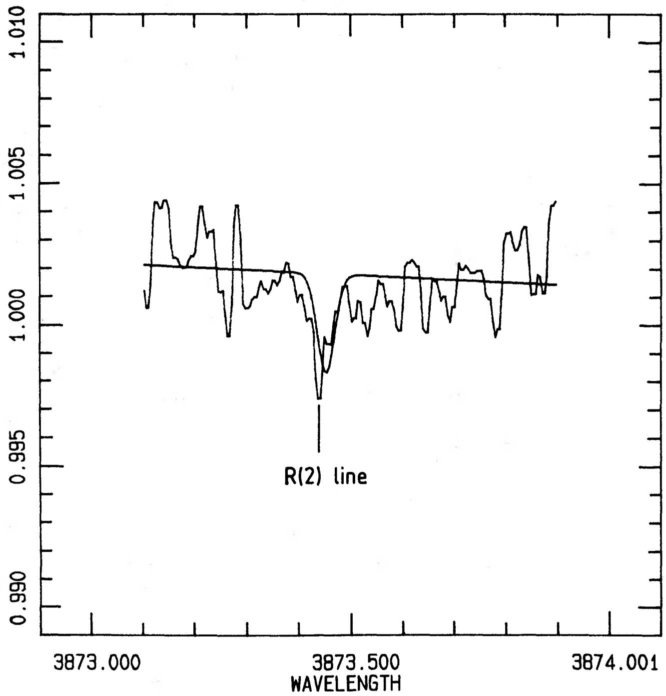

FIG. 2.—Spectrum of the $R(2)$ line of CN. Rest wavelength of this line is 3873.369 Å, but it occurs here at a wavelength of 3873.452 Å due to the Earth's motion relative to ζ Oph. Also shown is the fitted Gaussian whose center was determined from the positions of the $R(0)$, $R(1)$, and $P(1)$ lines. Small spike on the left of the line profile is noise.

the nights of 1985 July 15/16 and 19/20. Also shown in the figure is the Gaussian line profile that was fitted to the $R(2)$ line. The data shown in Figure 2 are the first certain detection of the $R(2)$ line in ζ Oph without the contamination of a telluric line. Both the observations of Hegyi, Traub, and Carelton (1974) and those of Meyer and Jura (1984) were contaminated by this telluric line at 3873.167 Å. We expect the earlier measurements of Hegyi, Traub, and Carelton (1972) were not blended with this telluric line.

Since the signal to noise in these spectra was not as good as we had hoped because of the coherent noise in the Reticon and the nonrandom effects of "cosmic rays," the equivalent widths of the $R(2)$ line reported in Table 1 were derived as follows. Sections of the spectra from several nights in 1985 were selected so as to contain the same pixels but not the same wavelengths for each pixel. This was possible, since the grating angle was changed from night to night. These nightly spectra were fitted to Gaussian profiles which had a center fixed in pixel space corresponding to the expected position of the $R(2)$ line for the selected night of interest and a fixed width determined from the $R(0)$ line. Since the $R(2)$ line was expected to occur at that position only for one of the nightly spectra, the difference between the average amplitude of the fitted Gaussians for the other nights and the amplitude for the night of interest yielded a measure of the equivalent width of the $R(2)$ line for that night. The results in Table 2 are for those nights when a definitive detection of the $R(2)$ line was observed.

Using the equivalent width of the $R(2)$ line, and following the same procedures described in the previous section to correct for curve of growth effects, we derive a value for the CBR temperature at 1.32 mm of 2.75 (+0.24, −0.29) K. This is summarized in Table 5.

d) Telluric Line at 3873.167 Å

Figure 3 shows our spectrum of a telluric line at 3873.167 Å for the night of 1984 August 6. Also shown in Figure 3 is a spectrum of comparable signal to noise for the night of 1984 August 8. For the night of August 6, the telluric line had an equivalent width of ~0.21 mÅ, whereas the equivalent width on the night of August 8 was less than ~0.05 mÅ. In addition to variations from night to night, we also found line strength variations during the individual nights in our 1984 data. If this line arises from OH or water vapor lines in the upper atmosphere, then this variability is not at all surprising.

This variability would seem to make it very difficult to extract a value for the $R(2)$ line strength from spectra where the $R(2)$ line is blended with the telluric line. Thus the only truly reliable way to determine the $R(2)$ line strength in ζ Oph is to observe during those times of year when the $R(2)$ does not fall at the same wavelength as this atmospheric feature.

IV. DISCUSSION AND CONCLUSIONS

In the last few years, second generation measurements of the cosmic background radiation have been performed from the centimeter region to the millimeter region, and provide measurements of the temperature with much improved accuracy compared with the previous measurements. In particular, for the microwave region between 12 and 0.33 cm, Smoot *et al.* (1985) report measurements confirming a blackbody spectrum of temperature 2.73 ± 0.04 K and limiting possible Compton distortions to less than 6%. In the peak of the spectrum from 3.51 to 1.01 mm, new photometric balloon-borne measurements of Peterson, Richards, and Timusk (1985) yield a temperature of 2.78 ± 0.11 K with no significant distortions from a thermal spectrum.

TABLE 5

CBR TEMPERATURE AT 1.32 MILLIMETERS

Line Ratio	T	$T_{\rm corr}$
$R(2)/R(1)$	2.78 (+0.26, −0.30)	2.75 (+0.25, −0.29)
$R(2)/P(1)$	2.75 (+0.28, −0.31)	2.74 (+0.27, −0.30)
$T_{\rm CBR}$	...	2.75 (+0.24, −0.29)

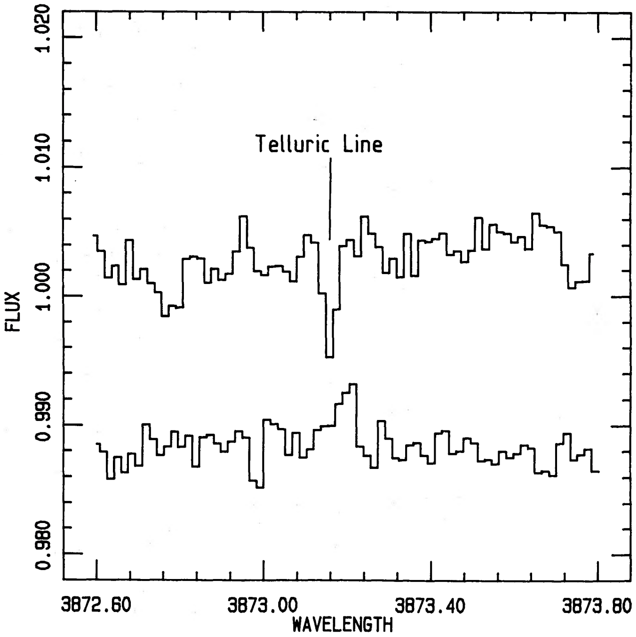

FIG. 3.—Spectrum of the telluric line at 3873.167 Å. Upper line is from 1984 August 6, and lower line is from 1984 August 8. Note the absence of the telluric line in the lower trace.

The value of 2.74 ± 0.05 K for the CBR temperature at 2.64 mm reported here agrees extremely well with the value from the multifrequency radiometer measurements of 2.73 ± 0.04 K reported by Smoot *et al.* (1985). On the other hand, it is not in good agreement with the Meyer and Jura (1985) results for ζ Oph corrected using our new curve of growth analysis. The value of 2.75 (+0.24, −0.29) K for the CBR temperature at 1.32 mm confirms the value reported by Meyer and Jura (1985) and agrees with the latest balloon-borne measurements of Peterson, Richards, and Timusk (1985). Since the CN measurements depend on very different techniques and involve very different systematic effects than the other measurements of the CBR temperature, the agreement between these different methods serves to increase our confidence in all the results.

By comparing the temperature at the peak (T_P) measured by Peterson *et al.* (1985) with that of the Rayleigh-Jeans region ($T_{\rm RJ}$) measured by Smoot *et al.* (1985), there is an excess at the peak of $y = (T_P - T_{\rm RJ})/2T_P < 3\%$. This can be compared to an excess of $y = 20\%$ reported earlier by Woody and Richards (1981). Possible origins for such distortions at the peak have been investigated by Rowan-Robinson, Negroponte, and Silk (1979), who pointed out that it could arise from primordial dust grains reemitting radiation from Population III stars at a redshift of $Z = 100$. Additional measurements near the peak of the spectrum are clearly required before a reliable determination of the existence of any spectral distortions can be confirmed. So far the CN data do not contribute to this question since the precision of the result at 1.32 mm is limited.

The precision of our result at 2.64 mm is limited by the uncertainty in the correction for local excitation of CN by electrons. Clearly the important experiment of Penzias, Jefferts, and Wilson (1972) of searching for emission from the interstellar clouds at 2.64 mm should be repreated for ζ Oph using modern millimeter wave antennae and receivers.

Our detection of the $R(2)$ line of CN in the direction of ζ Oph is not contaminated by a telluric line at 3873.167 Å. However, the signal-to-noise ratio of the $R(2)$ line is not yet high enough to yield an interesting measurement of the CBR temperature at 1.32 mm. Since the microwave and infrared techniques for studying the CBR temperature at 1.32 mm are very difficult and subject to very different sources of error, and since the CN results at 1.32 mm would be less effected by local excitation than at 2.64 mm, there is a strong motivation to improve the precision of the CBR temperature measurement at 1.32 mm by further observation of the CN molecule. It seems that an improvement by a factor of at least 3 and possibly a factor of 10 should be possible by further observations under good observing conditions with an improved detector.

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