Cosmic Background Radiation at 1.32 mm

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The position of the $R(0)$, $R(1)$, and $R(2)$ lines of the 3874-Å band of interstellar CN in the spectrum of the star ζ Ophiuchi were scanned with a Fabry-Perot interferometer. The Doppler width (full width at half-maximum) of the $R(0)$ line is 28 mÅ. At the expected position of the $R(2)$ line an absorption feature was found with an equivalent width of 0.077 ± 0.055 mÅ which implies a temperature of $2.9^{+3.4}_{-2.1}$ K for the cosmic background radiation at 1.32 mm. A conservative interpretation of the data is simply to give an upper limit (2σ) of 3.8 K to this temperature.

The long-wavelength region of the proposed 2.7-K cosmic blackbody spectrum[1] has been well established by ground-based radiometer measurements,[2,3] but observations on the short-wavelength side (< 1.9 mm) of the peak of the spectrum have yielded conflicting results.[4-7] At these wavelengths Earth's atmosphere is strongly absorbing, requiring that observations be performed from balloons and rockets. The measurements utilize bolometer and filter combinations, which intrinsically have very broad spectral responses and which therefore require some interpretation when applied to the rapid exponential falloff of the short-wavelength portion of the blackbody spectrum. In addition, balloon, and perhaps even rocket experiments, must contend with residual atmospheric emission.

Field and Hitchcock,[8] Thaddeus and Clauser,[9] and Shklovsky[10] have shown that the relative population of the $J=0$ and $J=1$ rotational states of interstellar CN molecules corresponds to a temperature around 3 K and that one would indeed expect this population to come to equilibrium with the cosmic background radiation at 2.64 mm (the wavelength corresponding to the $J=0$ and $J=1$ separation), collisional effects being negligible, or at most small. Extension of these measurements by Bortolot, Clauser, and Thaddeus[11] gave a more precise rotational temperature, $T_{10} = 2.83 \pm 0.15$ K, for the dense interstellar cloud in front of the star ζ Ophiuchi. A still further extension by Bortolot, Shulman, and Thaddeus[12] gives $T_{10} = 2.89 \pm 0.03$ K for the same cloud, and an accompanying calculation of collisional effects predicts that the actual brightness temperature of the background radiation at 2.64 mm is 0.07 ± 0.04 K less than T_{10}. Furthermore, measurements in the directions of eight other stars[13] also indicate a temperature of about 3 K, strengthening the case for the use of this indicator as a measure of the cosmic background radiation. For comparison, the radiometer measurements[2] of the longer wavelength part of the spectrum (8–32 mm) give a temperature of $2.68^{+0.09}_{-0.14}$ K.

The rotational temperature is measured from the intensities of absorption lines in the (0, 0) vibrational band of the $B^2\Sigma$-$X^2\Sigma$ electronic transition of CN, occurring around 3874 Å. The absorption lines are narrow and weak, which makes the measurements sufficiently difficult that lines due to higher rotational states than $J=1$ have not been detected. The higher states will be populated by stepwise excitation, the selection rule for dipole radiation being $\Delta J = \pm 1$. The energies of the states are proportional to $J(J+1)$, and the differences between them are proportional to J; therefore, the population of $J=2$ is determined by the intensity of the background radiation at 1.32 mm (and by the population of $J=1$) if collisional effects are indeed negligible. Bortolot, Clauser, and Thaddeus[11] set an upper limit on this population corresponding to a temperature $T_{21} < 4.7$ K. More recently, Bortolot, Shulman, and Thaddeus[12] find $T_{21} < 3.38$ K.

We recently made measurements of the R-branch lines $R(0)$, $R(1)$, and $R(2)$ of this CN band in the spectrum of ζ Ophiuchi, using the 60-in. telescope at the Mt. Hopkins station of the Smithsonian Astrophysical Observatory in June and July 1971. Our instrument is a three-etalon Fabry-Perot spectrometer (Fig. 1) of the PEPSIOS type,[14] which can easily gather all the light

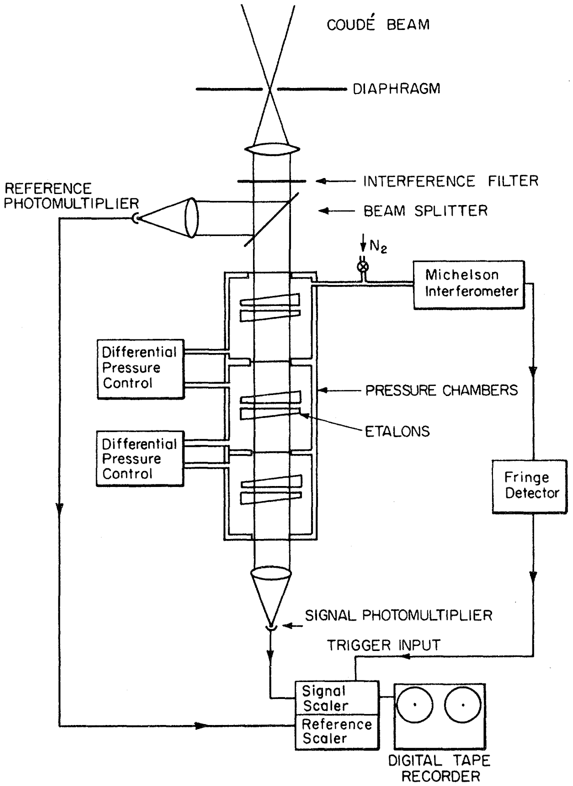
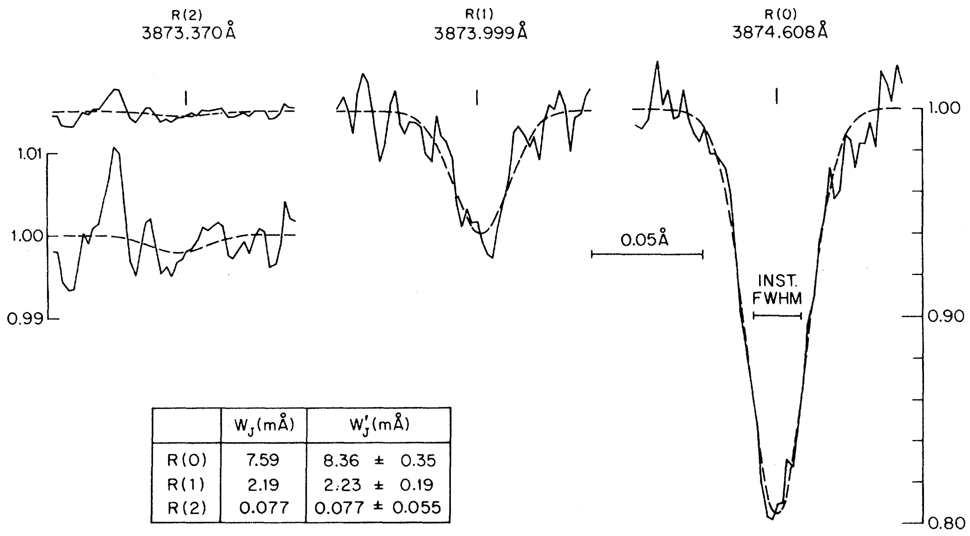


FIG. 1. Block diagram of the PEPSIOS interferometer and data-handling system.

from a stellar image at the resolving power of 1.8×10^5 that we used. The signal was detected by a cooled ITT FW-130 photomultiplier. A second photomultiplier looked via a clear-glass beam splitter at a portion of the light transmitted by the interference filter. The etalons are in sealed chambers, and the transmitted wavelength is scanned by admitting nitrogen gas. The pressure changes are monitored by counting the fringes of mercury light passing through an auxiliary fixed Michelson interferometer. Each fringe produces a trigger signal that causes a digital data-recording system to write on magnetic tape the signal and reference counts accumulated since the last fringe. The separation between fringes corresponds to 2.69 mÅ. Our actual spectral trace is the quotient of raw signal and reference counts (corrected for photomultiplier dark current), which provides normalization against variations in atmospheric transparency and in pressure-scanning rate. The instrument is calibrated in wavelength by scanning Fe lines from a hollow-cathode discharge. Scans of the solar spectrum show the parasitic light level to be less than 1%.

We made 277 scans, each of about 10-min duration and of 0.13 Å length, centered on the expected position of one of the R-branch lines of the CN band, $R(0)$, $R(1)$, or $R(2)$. The time was di-



	W_J(mÅ)	W_J'(mÅ)
R(0)	7.59	8.36 ± 0.35
R(1)	2.19	2.23 ± 0.19
R(2)	0.077	0.077 ± 0.055

FIG. 2. Observed spectra of the $R(2)$, $R(1)$, and $R(0)$ lines of the 3874-Å band of interstellar CN in front of the star ξ Ophiuchi, shown together with the best-fit Gaussian profiles (dashed lines). The $R(2)$ line is also shown on an enlarged intensity scale. The expected positions of the $R(2)$ and $R(1)$ lines, with respect to $R(0)$, are indicated by short tick marks at the continuum levels. Measured equivalent widths (W_J) are listed in the inset, along with corresponding values corrected for saturation (W_J'). Doppler shifts due to the motions of Earth (+2.6 to −6.7 km/sec) and of the interstellar cloud (−14.6 km/sec) have been removed; likewise, small continuum tilts, probably due to the interference filter, have been taken out of the spectra.

vided to give 203 scans of $R(2)$, 26 of $R(1)$, and 48 of $R(0)$. Our signal rate was about 15 counts/sec. Taking into account the Doppler shifts caused by Earth's spin and orbital motions, we added all the data for each line into a grand sum as shown in Fig. 2. The dashed-line curves are Gaussian absorption-line profiles and are generated as follows: First, we fit the $R(0)$ line by means of an iterative, nonlinear, least-squares program that determines its depth, width, and central position. The measured full width at half-maximum (FWHM) for the fitted line is 37 mÅ, while the width of our instrumental profile is only 22 mÅ. The latter was determined from scans of Fe lines and from theory and is well approximated by a Gaussian function. Assuming that the actual interstellar absorption profile is also Gaussian, with the form $\exp[-(c\Delta\lambda/b\lambda_0)^2]$, we find its FWHM to be 28 mÅ, corrected for saturation; this corresponds to a value of $b = 1.3 \pm 0.1$ km/sec (one standard deviation). This is the first direct measurement of this linewidth and is to be compared with the values determined from Na I, Ca II, and CH^+ lines in the ζ Ophiuchi spectrum by Herbig[15] from a curve-of-growth analysis: $b(\text{Na I}) = 2.4$ km/sec, $b(\text{Ca II}) = 1.5$ km/sec, and $b(\text{CH}^+) = 0.85$ km/sec. Using our measured value, we can determine the degree of saturation of the $R(0)$, $R(1)$, and $R(2)$ lines, which gives fractional corrections of 0.10, 0.02, and 0.0, respectively, on the equivalent widths.

We now proceed to fit the $R(1)$ and $R(2)$ lines, fixing their widths from the $R(0)$ data (taking saturation into account) and allowing the computer program to determine their depths and central positions. With respect to $R(0)$, the $R(1)$ and $R(2)$ lines appear where expected to within the fitting accuracy. The fitted $R(2)$ is displaced 5 mÅ from its expected position, and the uncertainty in finding its center is 12 mÅ; for $R(1)$ the value is 0.3 mÅ, with 1.3 mÅ uncertainty. The data are summarized in Fig. 2, the listed uncertainties being those estimated from the fitting program. These uncertainties agree well with simple statistical predictions that one may make, based on the numbers of counts recorded.

At this point we should like to decide whether the $R(2)$ scan actually shows an absorption line, or whether we should only state an upper limit. The fitting program simply shows that the residuals from the line indicated in Fig. 2 are in fact slightly smaller than those from a flat continuum. The indicated uncertainty on the equivalent width is a measure of the significance ($\sim 1.4\sigma$) of this assignment, which is marginal. We shall continue to speak about a "measurement," but do not insist that we have done more than establish the limits that we quote below.

To guard against spurious contributions, we scrutinized the numbers of counts in each channel of each scan. Points deviating by more than a given amount from the average value for the scan can be easily excluded from the general sum by setting both signal and reference equal to zero. Summing the data repeatedly, with more and more severe restrictions on the accepted points, revealed no systematic effects. Likewise, partial sums over different groups of nights showed nothing unexpected. Another check was to add the $R(2)$ data in the laboratory frame of reference, which displaced the interstellar lines from early and late observations by four linewidths because of the changing velocity of Earth. In this sum there appeared an essentially featureless spectrum, within the limits of statistical accuracy. Scans of a tungsten light source, intended as a check on the continuum response of the interferometer, showed a great deal of flickering that was not entirely compensated by our ratio-recording system; these scans could therefore not be used. We believe that this lack of compensation occurred because the tungsten source overfilled the instrument and produced scattered light that allowed the reference detector to see, effectively, a different part of the source than did the signal detector.

The positive spike at the left of the $R(2)$ position is an interesting feature that survives all the above-mentioned tests against spurious contributions. Its wavelength does not correspond to any atomic line in the Massachusetts Institute of Technology wavelength tables, and it is difficult for us to offer any reasonable explanation for its presence. One can imagine circumstances that would produce the $R(2)$ line itself in emission, but these seem very unlikely. Having no explanation for this feature, we must simply regard it as a manifestation of noise.

From our data we can derive the two temperatures of interest, T_{10} and T_{21}, which should be characteristic of the cosmic blackbody radiation at 2.64 and 1.32 mm, respectively. The values shown in Table I are computed from the relation[16] $W_J' = \text{const} \times (J+1) \exp[-J(J+1)Bhc/kT]$, where W_J' is the equivalent width of the $R(J)$ line (corrected for saturation) and B is the rotational constant[17] of CN ($v = 0$), 1.8909 cm^{-1}.

Our measurement of T_{10} agrees reasonably well

TABLE I. Observed intensity ratios, corrected for saturation, listed along with their associated uncertainties (1σ). The derived temperatures are given along with uncertainties for both 1σ and 2σ. We place parentheses around T_{21} to call attention to the weak statistical significance of the $R(2)$ line. A conservative interpretation of the data is that $T_{21} < 3.8$ K (2σ confidence level). (The 2σ lower limit is determined by requiring the temperature to be non-negative.)

J–J'	$\lambda_{JJ'}$ (mm)	$W_J'/W_{J'}'$	(1σ)	$T_{JJ'}$	(1σ)	(2σ)
1–0	2.64	0.267	0.025	2.70	2.83 2.57	2.95 2.45
2–1	1.32	0.035	0.025	(2.9)	3.4 (2.1)	3.8 0

with that of Bortolot *et al.*[13] We note here that we budgeted our observing time so as to maximize the time spent on $R(2)$ and $R(0)$, slighting $R(1)$ because of the existing data. Hence, their value of T_{10} is more accurately determined than ours. Our data on the $R(2)$ line suggest no departure from thermal equilibrium for the cosmic background radiation at 1.32 mm and set stringent limits on the possible excess of radiation at this wavelength.

Our present result, together with the most direct measurements,[6,18] suggests that the cosmic background radiation may indeed have a thermal spectrum extending to wavelengths at least as short as 1.32 mm. Recently, Muehlner and Weiss[18] made new observations resolving some of the earlier conflict in balloon measurements. Likewise, the rocket measurements of Blair *et al.*[6] show no evidence for much excess radiation in this region. Our measurement is a useful complement to these others in that it samples the radiation in a very narrow bandwidth and does so at a location far removed from the solar system.

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