UPPER LIMITS TO THE INTENSITY OF BACKGROUND RADIATION AT $\lambda = 1.32$, 0.559, AND 0.359 mm

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From observations of interstellar optical absorption lines of CN, CH, and CH^+ we are able to impose upper limits, at three wavelengths, on the intensity of background radiation in the interstellar medium. These limits are consistent with the existence of thermal background radiation at a temperature of ~3°K, but can be reconciled with the results of a recent rocket observation by Shivanandan, Houck, and Harwit only if the intense flux which they report is concentrated into a sharp line which happens to avoid the molecular resonances, or if this flux is of local origin.

Shivanandan, Houck, and Harwit[1] (SHH) have recently reported detection of intense background radiation in the wavelength interval from 0.4 to 1.3 mm with a rocket-borne far-infrared telescope. They find a total flux of 5×10^{-9} W cm^{-2} sr^{-1}, which yields a mean intensity of radiation $\bar{I}_\nu = 9.6\times10^{-14}$ erg cm^{-2} sec^{-1} sr^{-1} Hz^{-1} over the 5.2×10^{11} Hz between 0.4 and 1.3 mm. This represents on both a galactic and cosmological scale an enormous flux of radiant energy, far greater than the total flux expected from all galaxies[2] and nearly 100 times greater than that due to 3°K thermal radiation over this spectral range. Since a thermal spectrum is a critical prediction[3] of the hypothesis that the ~3°K background radiation observed at $\lambda = 3.3$ mm and longer wavelengths is a residue of the primeval fireball, this observation is potentially of major cosmological significance.

The interstellar optical absorption lines of CN, CH, and CH^+, however, impose upper limits to the intensity of radiation in the interstellar medium at $\lambda = 2.64$, 1.32, 0.559, and 0.359 mm[4,5] that are especially relevant to this question, since these wavelengths lie just to either side, and very near the middle, of the far-infrared channel of SHH (Fig. 2). Such limits derived from old Mt. Wilson spectra, that lie somewhat below their value for $\bar{I}_\nu$, have already been presented[4]; it is the purpose of this Letter to report the result of recent observations with the Lick Observatory 120-in. telescope that further depress these upper limits, and offer a grave obstacle to the idea that the flux observed by SHH is of galactic or cosmological origin.

ζ Ophiuchi ($V = 2.57$, MK-type 09.5V, $b^{\mathrm{II}} = +23°$) is the most favorable star visible from North America for detection of the faint interstellar lines of CN, CH, and CH^+.[6] By adding together on a digital computer 25 spectra of this star obtained by two of us (V.J.B. and P.T.) with the Coudé spectrograph of the 120-in. telescope, we have attained for these lines a signal-to-noise ratio about five times higher than provided by a single spectrogram. Figure 1 shows the result of the numerical synthesis in the vicinity of the strongest interstellar line of each of these molecules. The lines shown are members of the (0, 0) bands of the CN $B^2\Sigma$-$X^2\Sigma$, CH $A^2\Delta$-$X^2\Pi$, and CH^+ $A^1\Pi$-$X^1\Sigma$ electronic systems illustrated schematically in the top of Fig. 1. They are all formed in an interstellar cloud whose velocity with respect to the sun is -15 km/sec.[6] Precise rest wavelengths are listed in Table I.

The individual spectra were all obtained on baked IIa-0 emulsions at a dispersion of 1.3 Å/mm (the highest efficiently employed at the 120-in. Coudé) and were widened to 5 mm in order to store a large amount of information on each plate. A 25-μ projected slit width was used, which at this dispersion yields a resolving power in excess of 100 000.

To add the spectra together, the plate transmission and accompanying intensity calibrations were first automatically measured at intervals of one micron with a densitometer and recorded digitally on magnetic tape. The characteristic curve of the emulsion was then calculated by numerical interpolation for each plate in turn, allowing the required transformation from plate transmission (density) to intensity to be numerically performed in the computer. The second numerical trans-

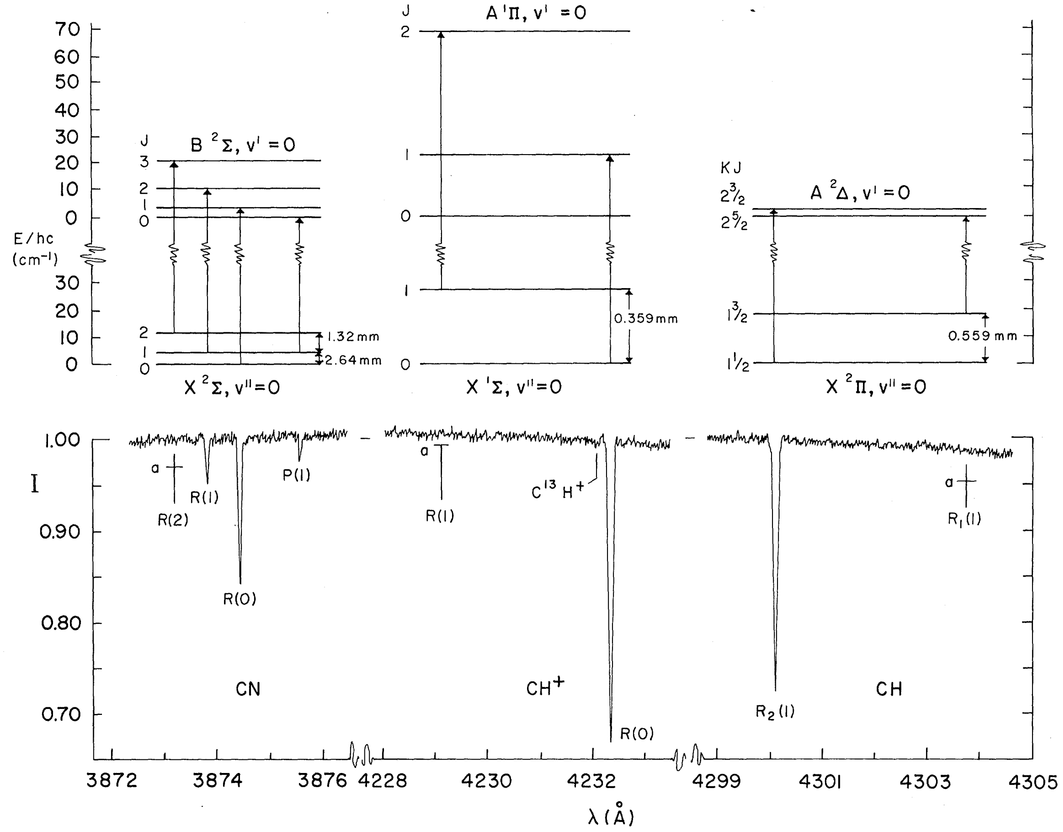

FIG. 1. The spectrum of ξ Oph in the vicinity of the strongest interstellar lines of CN, CH$^+$, and CH. Directly above each line the transition is shown schematically on a diagram of the relevant energy levels, all of which lie in the ground vibrational state of the molecule. "*a*" indicates the depth of the missing lines if the intensity of radiation in the interstellar medium at, respectively, $\lambda = 1.32$, 0.359, and 0.559 mm were 9.6×10^{-14} erg cm^{-2} sec^{-1} sr^{-1} Hz^{-1}.

formation of the data, from densitometer carriage displacement to wavelength, was done by similar digitizing of the Fe comparison spectra, using the strongest interstellar lines of CN, CH, and CH$^+$ as reference wavelengths. With the data in this form, final synthesis of the spectra was then a simple matter of numerical addition.

Table I. Wavelength, equivalent width, and optical depth of the −15-km/sec interstellar molecular lines in the spectrum of ξ Oph.

Molecule	Line	λ_{air} (Å)	W (mÅ)	τ
CN	$R(0)$	3874.608[a]	8.40	0.513
	$R(1)$	3873.998[a]	2.74	0.148
	$R(2)$	3873.369[a]	<0.43	<0.022
	$P(1)$	3875.763[a]	1.49	0.079
CH	$R_2(1)$	4300.321[b]	20.8	1.542
	$R_1(1)$	4303.947[b]	<0.44	<0.021
CH$^+$	$R(0)$	4232.535[c]	26.9	2.609
	$R(1)$	4229.337[c]	<0.59	<0.028

[a] F. A. Jenkins and D. E. Wooldridge, Phys. Rev. 53, 137 (1938).

[b] L. Gerö, Z. Physik 118, 27 (1941).

[c] A. E. Douglas and G. Herzberg, Can. J. Res. 20A, 71 (1942).

Numerical integration over the lines shown in Fig. 1 yields the equivalent widths listed in Table I. The upper limits of 0.43, 0.44, and 0.59 mÅ for the equivalent widths of CN $R(2)$, CH $R_1(1)$, and CH$^+$ $R(1)$ are in each case three times the standard deviation of the grain noise, and are the crucial data on which the conclusions reached in this Letter are based. A new interstellar line revealed by the plate synthesis at $\lambda = 4232.08$ Å underscores the conservative nature of these limits, since its equivalent width is 0.68 mÅ, or only slightly higher than the CH$^+$ $R(1)$ upper limit. [This line is probably λ4232 of C^{13}H$^+$. It falls at precisely the expected isotope shift −0.26 Å, and yields an abundance ratio C^{12}/C^{13} that agrees with the terrestrial value 89.[7]]

Calculation of excitation temperatures requires correction for the finite opacity of the interstellar lines. The curve of growth for interstellar CH^+ in the spectrum of ζ Oph has been recently obtained by Herbig,[6] and it is reasonable to assign his CH^+ Doppler linewidth parameter, $b = 0.85$ km/sec, to CN and CH as well, on the basis of their common radial velocity. Taking this value of b, the curve of growth analysis then yields the line strengths (optical depths) listed in the last column of Table I.

In the absence of additional interactions (collisions, resonance scattering of starlight, etc.), polar molecules such as CN, CH, and CH^+ will rapidly (in less than 10^6 sec) come into equilibrium with thermal background radiation, and the rotational or excitation temperature,

$$T_{ij} = h\nu_{ij}/k \ln(s/r), \tag{1}$$

calculated from any two optical absorption lines must, on thermodynamic grounds, be the temperature of the radiation. Here $h\nu_{ij} = E_i - E_j$, where $E_i > E_j$ are the rotational or (in the case of CH) fine-structure energies of the electronic and vibrational ground state, s is the ratio of theoretical line strengths for an optical line arising from level i to that arising from j (i.e., the ratio of the sums over initial and final states of the square of the transition matrix element), and r is the corresponding ratio of observed line strengths.

For isotropic but nonthermal background radiation and in the presence of additional interactions, T_{ij} in general will be a complicated function of the various transition rates. It remains, however, a rigorous upper limit to the brightness temperature $T_B(\nu_{ij})$ of background radiation at the frequency ν_{ij} as long as i and j are connected by an electric dipole transition. The frequency range over which this limit holds is the very narrow Doppler width, $\Delta\nu/\nu = \Delta\lambda/\lambda = v/c \sim 10^{-5}$, of the rotational transition.

The selection rule for the ground states of CN and CH^+ is $\Delta J = \pm 1$, while for CH, rather well represented by Hund's case (b), the selection rules are $\Delta K = 0, \pm 1$, $\Delta J = 0, \pm 1$.[8] Thus, the observed line strengths τ of Table I provide upper limits on the background intensity at the millimeter and submillimeter wavelengths 2.64, 1.32, 0.559, and 0.359 mm indicated in Fig. 1. The requisite theoretical line-strength ratios s are obtained for CN and CH^+ from the Hönl-London relations[9]; for CH the calculation is slightly more elaborate since due account must be taken of the slight departure of the ground-state coupling scheme from Hund's case (b). For these ratios, and for the brightness and excitation temperatures which then follow from Eq. (1) and the data of Table I, we find

$$\text{CN } R(1)/R(0){:}\quad s = 2, \quad T_B(2.64\text{ mm}) \leqslant T_{10} = 2.82^\circ\text{K}; \tag{2a}$$

$$\text{CN } P(1)/R(0){:}\quad s = 1, \quad T_B(2.64\text{ mm}) \leqslant T_{10} = 2.91^\circ\text{K}; \tag{2b}$$

$$\text{CN } R(2)/R(1){:}\quad s = \tfrac{3}{2}, \quad T_B(1.32\text{ mm}) \leqslant T_{21} < 4.74^\circ\text{K}; \tag{2c}$$

$$\text{CH } R_1(1)/R_2(1){:}\quad s = 1.524, \quad T_B(0.559\text{ mm}) \leqslant T_{\frac{13}{2},\frac{11}{2}} < 5.43^\circ\text{K} \approx 9/5\ [\text{case (b)}]; \tag{2d}$$

$$\text{CH}^+\ R(1)/R(0){:}\quad s = \tfrac{3}{2}, \quad T_B(0.359\text{ mm}) \leqslant T_{10} < 8.11^\circ\text{K}. \tag{2e}$$

The weighted mean value for T_{10}(CN) obtained from (2a) and (2b) is $T_{10} = 2.83^\circ$K, with an uncertainty that we estimate to be 0.15°K. The grounds for believing that this is the actual value of the brightness temperature of the background radiation at $\lambda = 2.64$ mm, rather than only an upper limit, have been discussed elsewhere.[4,5] The most compelling evidence is the invariance of T_{10}(CN) in the direction of at least nine stars, and its precise agreement in the two best cases, that of ζ Oph considered here and ζ Per,[4] with the series of direct measurements of T_B made by Wilkinson and his collaborators[10] at $\lambda = 3.3$ mm and longer wavelengths.

Equations (2c)-(2e), however, are the principal object of our attention here. These yield as upper limits on the intensity of background radiation $I_\nu(1.32\text{ mm}) < 1.92 \times 10^{-14}$, $I_\nu(0.559\text{ mm}) < 2.00 \times 10^{-14}$, and $I_\nu(0.359\text{ mm}) < 6.19 \times 10^{-14}$ erg $\text{cm}^{-2}\ \text{sec}^{-1}\ \text{sr}^{-1}\ \text{Hz}^{-1}$, which are higher than the intensity of 2.83°K thermal radiation by factors of 5.1, 77, and 1×10^4, respectively. An increase in signal to noise by these respective factors for the CN, CH, and CH^+ lines would thus be necessary in order to detect the missing lines, if the background radiation is indeed thermal. For CN this could be achieved by an extension of the

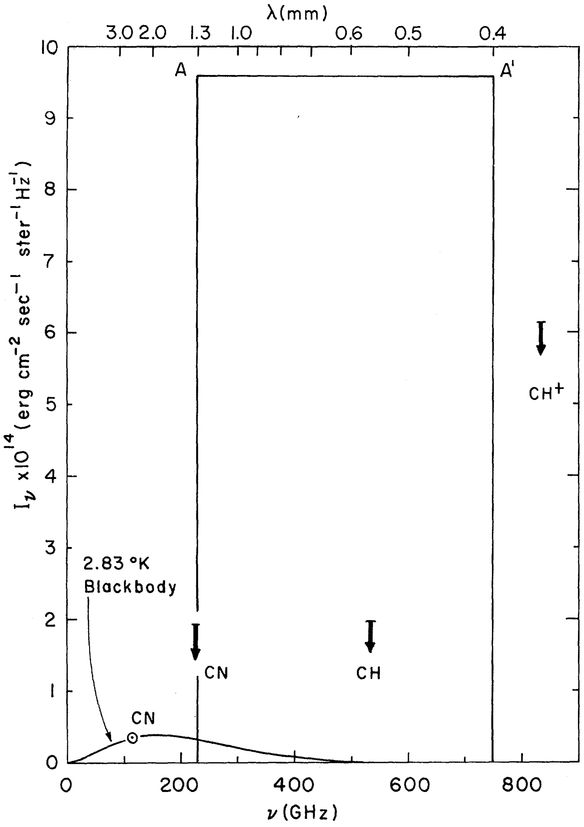

FIG. 2. Limits on the intensity of radiation I_ν in the interstellar medium. The scale is linear, and thus the area under the line AA' represents the flux of 5×10^{-9} W cm^{-2} sr^{-1} observed by SHH.

present tecnhique, and for CH it might barely be possible with photoelectric detection and very long integration times. We note, however, that the radiation from galactic dust is likely to be comparable with 2.83°K thermal radiation at $\lambda = 0.559$ mm, and perhaps two orders of magnitude more intense than such radiation at $\lambda = 0.359$ mm.

Figure 2 shows these upper limits on a linear scale, and the point $I_\nu(2.64\text{ mm}) = 0.370\times10^{-14}$ erg cm^{-2} sec^{-1} sr^{-1} Hz^{-1} deduced from the mean value $T_{10}(\mathrm{CN}) = 2.83$°K. The flux 5×10^{-9} W cm^{-2} sr^{-1} observed by SHH is represented by the area under the line AA'. Since its mean value is nearly five times greater than, in particular, the CH limit at $\lambda = 0.559$ mm, we are forced to conclude that this flux, unless concentrated into a sharp line which by coincidence avoids the molecular resonances, is of quite local origin (i.e., does not extend as far as the -15-km/sec cloud in front of ζ Oph). We underscore the fact that all the limits which we obtain from interstellar molecules, however, are compatible with strictly thermal background radiation at $T = 2.83$°K.

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[2] J. R. Shakeshaft and A. S. Webster, Nature 217, 339 (1968); F. J. Low and W. H. Tucker, Phys. Rev. Letters 21, 1538 (1968).

[3] P. J. E. Peebles, Astrophys. J. 153, 1 (1968).

[4] J. F. Clauser and P. Thaddeus, in Topics in Relativistic Astrophysics, edited by S. P. Maran and A. G. W. Cameron (Gordon and Breach Publishers, Inc., to be published).

[5] P. Thaddeus and J. F. Clauser, Phys. Rev. Letters 16, 819 (1966); G. B. Field and J. L. Hitchcock, Phys. Rev. Letters 16, 817 (1966).

[6] G. H. Herbig, Z. Astrophys. 68, 243 (1968).

[7] V. J. Bortolot, Jr., and P. Thaddeus, to be published.

[8] See, for example, C. H. Townes and A. L. Schawlow, Microwave Spectroscopy (McGraw-Hill Book Company, New York, 1955). Although the ground state of CN is $^2\Sigma$, the small ρ doubling of the levels is too small to be resolved optically, and therefore, on the basis of spectroscopic stability, we assign quantum numbers and calculate intensities as though the ground state were $^1\Sigma$,

[9] See, for example, G. Herzberg, Spectra of Diatomic Molecules (D. Van Nostrand Company, Inc., New York, 1959), 2nd ed.

[10] P. E. Boynton, R. A. Stokes, and D. T. Wilkinson, Phys. Rev. Letters 21, 462 (1968); R. A. Stokes, R. B. Partridge, and D. T. Wilkinson, Phys. Rev. Letters 19, 1199 (1967); David T. Wilkinson, Phys. Rev. Letters 19, 1195 (1967).