EXCITATION TEMPERATURES FOR THE CN EMISSION FROM THE LOW CHROMOSPHERE

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Summary

Microphotometer tracings have been made of the region of the CN 3883 A band system, which is a prominent feature of the flash spectrogram obtained by Redman at the 1952 eclipse. The CN bands are seriously affected by blending, but enough unaffected lines have been found to enable the rotational intensity distribution in the o--o band to be measured at three heights below about 400 km. Self absorption is important, particularly at the band heads, and its effects have been estimated. The measurements indicate a negative excitation temperature gradient, the temperature at about 400 km being \( \approx 4500^\circ \), and the value of the gradient uncertain. However, the CN emission may not be inconsistent with the positive kinetic temperature gradient of de Jager's most recent chromospheric model, if departures from local thermo-dynamical equilibrium and the imperfection of the observational data are taken into account.

1. Introduction.—Until quite recently it was thought that there was strong evidence both for a high (\( \sim 30000^\circ \)) and a low (\( < 10000^\circ \)) kinetic temperature for the low chromosphere. The conflicting evidence has been summarized and discussed by van de Hulst (1953). While a low temperature is now generally accepted, its exact value and gradient are still uncertain. One of the most prominent features of the flash spectrogram obtained by Redman at the total eclipse of 1952 February 25 is the 3883 A band system of cyanogen. In principle, these bands supply an excellent means for obtaining accurate temperatures, as the relative intensities of the lines composing the bands and of the bands themselves depend strongly on the temperature. However, in practice, measurements of the intensity of the CN emission in the flash spectrum yield directly only the relative populations of different energy levels of the molecule, and hence an effective excitation temperature. The corresponding kinetic temperature is then a matter of interpretation in terms of the physical conditions assumed to exist in the chromosphere.

Determinations of molecular excitation temperatures in the low chromosphere have already been published by Blackwell (1955), Pecker and Athay (1955) and Parker (1955). Using Redman's 1940 eclipse spectrogram (Redman 1942) Blackwell measured lines of the weak 4216 A CN and 4300 A CH bands, neglecting the band heads. Pecker and Athay's discussion is confined to the 3883 A CN band head on the High Altitude Observatory's 1952 slitless spectrograms, and is open to serious criticism. Parker, working with the Mount Wilson 75-ft spectrograph outside eclipse, had the advantage of a high resolution, but needed to employ a difficult correction for the contribution of photospheric radiation (both scattered and direct) to the intensities of the Swan C\(_2\) bands. These authors' results are
discussed in the light of the present work in Section 7. The excitation temperatures determined in this paper are based upon the largest dispersion slit spectrogram yet obtained at an eclipse. In the analysis, both band heads and individual lines have been considered and allowance has been made for self-absorption.

2. Observational material.—Only the essential details of the instrument used and the procedure followed at the 1952 eclipse need be noted here, as a full account has already been given by Redman (1953, 1955). The slit spectrograph employed a 15000 lines per inch 6-in concave grating of 21-ft radius of curvature in a Wadsworth mounting. The resulting dispersion in the wave-length range 3400 A to 4100 A was 2.4 A/mm. The instrumental profile was determined at the eclipse site by means of a mercury isotope lamp. The excellent flash spectrogram used in the present work was obtained during an exposure of 1.5 sec immediately preceding third contact, the coolostat being rated to follow the Moon. An attempted relative intensity calibration on the eclipse plate itself was unsuccessful. Four photospheric spectrograms were therefore obtained on another plate from the same batch with a Hilger rhodium-on-quartz step wedge in front of the slit. The two plates were processed identically and may be assumed to possess the same characteristics. The transmission factors of the step wedge were determined at the National Physical Laboratory.

A portion of the flash spectrogram in the region of the principal CN band heads is reproduced in Plate 7. The variation in intensity perpendicular to the direction of the dispersion is due partly to irregularities on the limb of the Moon and dust on the jaws of the slit, partly to the fact that positions along the slit represent, in some measure, heights above the photosphere, and partly to the spicular structure of the chromosphere. Initially, it is sufficient to denote positions along the slit by the arbitrary system of "levels" indicated in Plate 7, as the analysis of each level is independent. Only when correlating the results from different levels is it necessary to know even their relative heights, which are easily obtained. The determination of the actual effective chromospheric heights is a difficult problem, but they are necessary only for the final interpretation of the results. During the exposure the slit, following the Moon, scans the chromosphere at a rate of about 400 chromospheric km/sec. The "seeing" was estimated by Redman to be 2", corresponding to 1400 chromospheric km. As a result, the recorded emission originates in varying proportions from slices right through the chromosphere, covering a range of about 2000 km of the chromosphere and the (occulted) photosphere. A geometrical determination of effective heights is therefore impossible. Redman and Suemoto (1954), in their study of the metal lines in this spectrogram, compared the relative intensities of some prominent lines with their relative intensities on the slitless spectrograms obtained by Houtgast (1953) at the same eclipse. In this way they estimated that Levels 1, 2 and 3 correspond to heights < 50 km, < 100 km and \( \approx 600 \) km, respectively. According to Houtgast the intensity gradient in the chromosphere is much steeper for the CN 3883 A band head than it is for the metal lines. The effective heights of the CN emission must therefore be somewhat less than the above figures. The adopted heights for the three levels, of which an analysis has subsequently been made, are: Level 1 \( \approx 0 \) km; Level 2 \( \approx 50 \) km; Level 3 \( \approx 400 \) km.

In order to obtain the intensities of the CN lines in the flash spectrum, tracings of Levels 1, 2 and 3 were made with the Cambridge Observatories’ recording densitometer. Levels 2a and 3a proved to be unsuitable because of the weakness
of the CN lines and Levels 1a and 1b because of their high background intensities. The characteristic curve of the plate was obtained from tracings made across the step wedge spectra, no change with wave-length being detectable. A mean characteristic curve for the microphotometer tracings was then derived, the range of measurable intensities being represented by 100 units on an arbitrary relative intensity scale. Fluctuations in the dark current and clear glass transmission, etc., produce an estimated maximum error of ± 2 units in intensities obtained from this mean curve. The microphotometer tracings were reduced to direct intensities at the Dominion Astrophysical Observatory, B.C., using the Beals (1944) intensitometer. The completed records have an amplitude of 10 in., corresponding to 100 units on the above scale. At various points they were checked with a point-by-point reduction and found to be very satisfactory. The record of Level 1 in the region of the CN o–o band head is reproduced in Fig. 1.

![Graph showing CN o–o band head](image)

**Fig. 1.**—Reproduction of the region of the CN o–o band head on the direct intensity record of Level 1. Theoretical positions of individual lines are indicated below.

From measurements of the positions of 75 sharp lines, whose identifications and wave-lengths were obtained from the Revised Rowland Table of photospheric wave-lengths (St John 1928), the dispersion of the plate was found to be linear over the range covered by the CN bands. The same lines were identified on the intensity records, the dispersion obtained from their measured positions being 82.86 mm/A, showing the magnification of the records over the plate to be just less than 200 times. The maximum error in the position of a line on the records was estimated to be ± 4 mm (± 0.05 Å).

3. **The ultra-violet CN bands.**—The ultra-violet bands of cyanogen arise from the transition between the $X^2Σ^+$ and $B^2Σ^+$ electronic states of the CN molecule. The sequence $Δv=0$ forms a series of bands degraded towards the violet with its head at 3883 Å, the head of the o–o band. In $2Σ$ electronic states the rotational levels with quantum number $K$ are split into two components.
The region of the principal CN band heads in Redman's 1952 eclipse spectrogram.

Enlargement × 9 (approx.).

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with quantum numbers \( J = K + \frac{1}{2} \). As a result of the selection rules \( \Delta K = \pm 1 \), \( \Delta J = 0 \), \( \pm 1 \), a \( ^3\Sigma - ^3\Sigma \) band consists of a doublet \( P \) branch, a doublet \( R \) branch, and two satellite \( P \)-form and \( R \)-form \( Q \) branches. The satellite branches are very much less intense than the \( P \) and \( R \) branches, so the CN bands are often treated as \( ^1\Sigma - ^1\Sigma \) bands \( (J = K) \), each \( P \) and \( R \) branch doublet being considered as a single line at the centre of the doublet. The relations governing the wave-numbers of the individual lines in a \( ^1\Sigma - ^1\Sigma \) band are given in the standard texts (e.g. Herzberg 1950). The \( P \) and \( R \) branch relations may be expressed as one equation with the "running number" \( m \) as argument:

\[
\sigma(m) = A + Bm + Cm^2 + Dm^3 + Em^4 + \ldots, \tag{3.1}
\]

where for the \( P \) branch \( m = -K^* \),

\[
\text{and for the } R \text{ branch } m = K^* + 1, \tag{3.2}
\]

and the constants \( A \ldots E \) are easily determined functions of the rotational constants of the molecule. The most recent rotational constants, due to Douglas and Routly (1955), have been adopted. The values of the constants are such that for the most important bands of the 3883 A band system, \( \sigma(m) \) is a minimum at \( m \simeq -30 \), so that a band head is formed in the \( P \) branches near \( P \) (30).

The most extensive laboratory measurements of the CN 3883 A band system are still those made by Uhler and Patterson (1915). There is no systematic difference between their wave-lengths and those recently published by Weinard (1955): as the random differences are generally less than 0.005 A, which is only one-tenth of the possible error in the intensity records, the accuracy of the published wave-lengths is more than sufficient for the purpose of identifying CN lines on the records.

For each of the \( o-o \ldots 4-4 \) bands, the gap corresponding to the forbidden line \( P(0) \) has been detected, so the quantum numbering of the \( R \) branches, and the \( P \) branches as far as the band heads, is simply obtained by following the regular series of lines. The numbering of the returning portions of the \( o-o \) and \( 1-1 \) \( P \) branches has been obtained by Smit-Miessen and Spier (1942); they compared Uhler and Patterson’s measures with values computed from equation (3.1), whose coefficients were determined from the wave-numbers of lines already identified. The identifications have been confirmed by computing the coefficients in (3.1) independently from Douglas and Routly’s band constants. The \( P \) branches of the other bands are too greatly obscured in the flash spectrum for identifications to be necessary.

The positions of all Uhler and Patterson’s lines whose quantum numbering had been determined were marked on the intensity records. The general concentration of lines in the ultraviolet region of the flash spectrum is so great that even the Rowland table of photospheric wave-lengths does not contain them all. It cannot be determined with certainty, therefore, that any particular CN line is unblended. For this reason, and also because of the irregularities in the dispersion of the records, certain identification of lines on the records as CN lines is not possible.

4. Intensity distribution in CN bands in emission.—As the flash spectrum does not possess an absolute intensity calibration, the present work is concerned only with the relative intensities of the lines emitted as a result of the transition \( B^2\Sigma \rightarrow X^2\Sigma \) at any particular temperature. Assuming a Boltzmann distribution
of molecules amongst the energy states corresponding to an excitation temperature \( T \), the relative intensities of lines emitted as a result of transitions from the levels \((\nu', K')\) of the upper state to the levels \((\nu'', K'')\) of the lower state are given by

\[
I_{\nu'K'-\nu''K''} = C \sigma_{\nu'K'-\nu''K''}^4 P_{\nu'-\nu''} \exp \left( G'(\nu') \frac{\hbar c}{kT} \right) S_{K'-K''} \exp \left( -F'_{\nu'}(K') \frac{\hbar c}{kT} \right),
\]

where \( C \) is a constant determined by the transition, the temperature and the total number of molecules,

- \( \sigma_{\nu'K'-\nu''K''} \) is the wave-number of the line,
- \( P_{\nu'-\nu''} \) is the vibrational transition probability,
- \( S_{K'-K''} \) is the rotational line strength, and
- \( G'(\nu'), F'_{\nu'}(K') \) are the vibrational and rotational term values of the upper state, dependent upon the band constants. The relative intensities of the rotational lines in a band of the \( \Delta \nu = 0 \) sequence are therefore given by

\[
I_{K'-K''} = \text{constant} \sigma_{K'-K''}^4 S_{K'-K''} \exp \left( F'_{\nu'}(K') \frac{\hbar c}{kT} \right).
\]

The line strengths for the various branches of \( ^3\Sigma^- \rightarrow ^3\Sigma^- \) and \( ^1\Sigma^- \rightarrow ^1\Sigma^- \) bands have been derived by Mulliken (1927). When \( K' \geq 5 \), the intensities of the satellite \( Q \) branches of a \( ^3\Sigma^- \rightarrow ^3\Sigma^- \) band are negligible, and the combined intensity of the two components of a \( P \) or \( R \) branch doublet differs by less than 1 per cent from the intensity of the corresponding singlet in a \( ^1\Sigma^- \rightarrow ^1\Sigma^- \) band. The intensities of the CN lines are therefore given to a sufficient approximation by (4.2), where \( S_{K'-K''} \) now represents the line strengths for \( ^1\Sigma^- \rightarrow ^1\Sigma^- \) bands, i.e.

\[
\text{for the } P \text{ branch } S_{K'-K''} = 2(K' + 1) \quad \text{and for the } R \text{ branch } S_{K'-K''} = 2K',
\]

and \( \sigma_{K'-K''} \) and \( F'_{\nu'}(K') \) now refer to the centres of the doublets.

A useful modification of (4.2) is obtained by taking logarithms:

\[
\ln \left( \frac{I_{K'-K''}}{\sigma_{K'-K''}^4} \right) = \text{constant} - F'_{\nu'}(K') \frac{\hbar c}{kT} \cdot \frac{1}{T}.
\]

Plotting \( \ln \left( I_{K'-K''}/\sigma_{K'-K''}^4 \right) \) against \( F'_{\nu'}(K') \frac{\hbar c}{kT} \), where the \( I's \) are measured intensities, a least-squares method yields the slope \( -1/T \) of the straight line relation, and hence the temperature directly.

The relative intensities of homologous lines in the \( \nu-\nu \) and \( \sigma-\sigma \) bands can be obtained from (4.1). Taking \( F'_{\nu'}(K') = F_0'(K') \) and substituting the wave-numbers of the respective band origins for those of the individual lines (these approximations are justified by the lower accuracy of the measurements subsequently made on the \( 1-1 \ldots 4-4 \) bands and the uncertainties in the values of the vibrational transition probabilities), the relation simplifies to

\[
\frac{I(\nu, K)}{I(\sigma, K)} = \frac{\sigma_{\nu-\nu}^4 P_{\nu-\nu}}{\sigma_{\sigma-\sigma}^4 P_{\sigma-\sigma}} \exp \left( -G'(\nu) \frac{\hbar c}{kT} \right) \exp \left( -G'(\sigma) \frac{\hbar c}{kT} \right).
\]

The transition probabilities adopted are those computed by Pillow (1953). The small differences between these and the more recent laboratory values of Floyd and King (1955) have no significant effect on intensities calculated from (4.5).
5. Determination of effective excitation temperatures

5.1. Preliminary estimates.—As the CN lines are strongest on the intensity records of Level 1, this level was selected for preliminary measurements. An immediate difficulty is the presence of a continuous background caused partly by the continuous radiation from the chromosphere itself, and partly by scattered photospheric radiation from the first traces of a Baily's bead (see Redman 1955). The background is distorted in many places by the overlapping of large numbers of faint lines and the wings of strong lines, and by errors in the photometric reductions. Superimposed upon it are fluctuations due to the photographic grain and dust on the plate. Photometric errors due to the use of a mean characteristic curve in the reduction to direct intensity can be reduced by drawing the apparent rather than the mean continuous background, assuming it to vary smoothly between those regions of the spectrum apparently not enhanced by overlapping weak lines. The background was determined separately for two limiting cases: the lowest possible background, which assumes that the major small-scale irregularities are weak lines, and the highest possible background, which assumes that these irregularities are all "noise". An analysis based on an estimation of the exact position of the background has no advantage over an interpolation between the results obtained from the two limiting cases considered.

It appears from the intensity records of Level 1 (Fig. 1) that the $o-o$ band head is probably affected by self-absorption; the peak intensity of the band head is very little greater than the peak intensities of the pairs of lines nearby. The simplest method of obtaining a preliminary estimate of the temperature therefore appeared to be to find the distribution of intensities amongst the rotational lines of the $o-o$ band and make use of (4.2). The intensities of all the lines in positions where $o-o$ band lines were predicted were measured with a planimeter, assuming the lowest possible background for this preliminary determination. The total area of each $P$ branch pair (formed by the near coincidence of lines of the proceeding and returning portions of the $P$ branch) and the total intensity of the band head, in three sections, were also measured. The best method of representing the measures graphically is that adopted in Fig. 2, the abscissa of which is a linear scale in the running number $m$ reflected at $m = -28$, the head of the $P$ branch. This makes possible the representation of the intensities of the $P$ branch pairs, since the nearly coincident components of the pairs appear as exactly coincident in the figure. From $m = -21$ to $-35$ the separation of the individual components of the doublets is of the same order as that of the doublets themselves (see Fig. 1), so the band head would not exhibit the "pair" formation even with complete resolution of the lines. However, as it is only possible to measure the total intensity of the band head, the representation is not rendered invalid, and it is convenient for comparing measured and theoretical intensity distributions.

No account was taken of possible blends, so the intensities in Fig. 2 are in effect maximum intensities. As perturbed lines were omitted, the plotted points should all lie on or above (for unblended and blended lines, respectively) the intensity distribution curve for the appropriate temperature. The intensity curves for three temperatures, calculated by means of (4.2), are drawn in Fig. 2 to scales such that all the plotted points lie on or above the curves. Comparing the three curves with the measured intensities, it appears that very few of the measured lines are unblended. The distribution for $7000^\circ$ fits the measures best but requires considerable self-absorption at the band head. The conclusion that the band head is depressed by self-absorption can be avoided by assuming a
temperature of 10000°, but this would necessitate large blending corrections for all the strong lines and no correction at all for a number of weak lines. The effective rotational temperature therefore appears to be in the region of 7000°, not as high as 10 000°, and probably not as low as 4000°.

An approximate blending correction to the measured intensities was derived from consideration of the average intensities of lines immediately to the red of the o–o band head. However, the corrected intensities merely confirm the indication of Fig. 2 of a rotational temperature in the region of 7000°.

![Graph showing CN o–o band, Level 1: uncorrected line areas (assuming lowest continuous background). In this and subsequent figures the points "o" represent the areas (= intensities) of the corresponding lines or "pairs" of lines. The area of each rectangle equals the total area (= total intensity) of the corresponding group of unresolved lines.](image)

Because of the suspected depression of at least the o–o band head by self-absorption, it would be unwise to attempt to obtain an estimate of the effective vibrational temperature by comparing the intensities of the band heads. The P branches are badly obscured, but the intensities of lines in the R branches of the various bands may be compared, utilising the relations (4.2) and (4.5). The areas of all the lines in positions where the R branch lines of the 1–1...4–4 bands had been predicted were therefore measured, no attempt being made to allow for blends. The measured intensities were plotted on diagrams of running number versus intensity, together with the intensity distributions corresponding to those already drawn in Fig. 2 for the o–o band. While the 7000° curves agree best with the measures, neither the curves for 4000° nor those for 10 000° violate the condition that all the measured points should lie on or above the curves.

5.2. Computed CN line profiles.—It is not possible to deduce reliable CN line profiles from the intensity records because all the CN lines are unresolved doublets and only a very few appear to be free from blends. However, it is possible to compute profiles for an assumed temperature and turbulence of the emitting gas, knowing the characteristics of the recording apparatus. It may safely be assumed that the effects of collision and radiation damping are negligible for all except the strongest chromospheric lines. The emitted CN line with wavelength λ₀ will therefore have a Doppler profile with equation

\[ I(\lambda) = C \exp \left\{ - \left( \frac{\mu}{2RT} + \frac{1}{\xi \delta} \right) \frac{c^2}{\lambda^2} (\lambda - \lambda_0)^3 \right\}, \]  

where \( \mu \) is the molecular weight, \( T \) is the kinetic temperature, and the probability

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of a molecule having a turbulent velocity in the line of sight between $\xi$ and $\xi + d\xi$ is proportional to $\exp(-\xi^2/\xi_0^2) d\xi$. A half-width of 0.073 A was obtained for all CN lines on computing the profile (5.1) with the following assumptions: the kinetic temperature equal to the estimated effective excitation temperature, i.e. 7000°, a turbulence $\xi_0 = 2.7$ km/sec, as determined by Redman and Suemoto (1954) from metal lines at the identical Level 1, $\lambda_0$ constant for all CN lines.

The effect of the apparatus function of the spectrograph and the width of the microphotometer slit on the emitted line profile was determined by the method of Voigt functions described by van de Hulst and Reesinck (1947). The resulting computed profile of a CN line on the intensity records of Level 1 has a half-width of 8.9 mm (0.11 A). The variation in the computed profile with wave-length is negligible for the wave-length range covered by the CN bands. The total variation in the computed half-width, due to an assumed probable error of $\pm 0.5$ km/sec in the adopted $\xi_0$ and to a temperature range of $\pm 3000^\circ$ about the adopted 7000°, is less than $\pm 10$ per cent. The computed CN line profiles are thus relatively insensitive to the adopted kinetic temperature, and can be used to determine the intensities of the CN lines on the records more accurately.

5.3. Effective excitation temperature of Level 1.—For the reasons pointed out earlier, the predicted line positions may be in error by $\pm 4$ mm, and the fact that the majority of CN lines are affected by blending means that in most cases the exact line positions cannot be determined more accurately by inspection. Thus in each case lines having the computed profiles were constructed within $\pm 4$ mm of the predicted position such that the resulting line intensity was the maximum possible consistent with the feature on the intensity record (the two components of the doublets were taken to have equal intensities). For those doublets unresolved by Uhler and Patterson, theoretical doublet separations were obtained from a diagram of the separations of the resolved doublets plotted against the rotational quantum number $K''$: the mean curve through the plotted points was extrapolated back to $K'' = 0$ in accordance with the relations governing the splitting of the rotational energy levels (Mulliken 1930).

As the half-widths of all the CN lines are the same, their intensities are proportional to their central intensities. Hence the height of the central ordinate of either component of a constructed doublet may be used instead of its area as a measure of its intensity. The intensities of the constructed lines of the o—o band are plotted in Fig. 3 (heavily blended lines are omitted). Individual lines could not be constructed in the unresolved portion of the band head, so its previously measured area was converted to the new intensity units by determining the area of a standard line profile.

The intensities in Fig. 3 are once again maximum intensities, apart from six lines (two of these constituting a P branch pair) which appear to be unblended and whose intensities may therefore be considered accurate. A least-squares solution of a plot of $\ln \left[ I/\sigma K' \right]$ versus $F_0'(K')h\epsilon/k$ for the three accurate R branch lines R(14), R(49) and R(74), gives $T = 7300^\circ$. The probable error, $\pm 200^\circ$, does not give such a good idea of the likely maximum or minimum temperatures as the scatter $\pm 500^\circ$, obtained by assuming each pair of points in turn to be correct. The computed temperature distributions for 7300° and 7800°, shown in Fig. 3, fit the R branch intensities almost equally well, but the band head again appears to be depressed by self-absorption.
Comparing the corresponding computed intensity distributions in the 1–1...4–4 bands with the measured intensities of the constructed R branch lines, there appears to be no appreciable difference between the agreement for 7300° and 7800°, which is good in each case. Thus there is no detectable difference between the effective rotational and vibrational temperatures.

Fig. 3.—CN 0–0 band, Level 1: intensities of constructed lines (assuming lowest continuous background).

Fig. 4.—CN R branches, Level 1: intensities of constructed lines (assuming highest continuous background).
The effect of changing the assumed height of the continuous background was investigated by repeating the above procedure with the highest possible background level previously determined. A diagram similar to Fig. 3 was obtained, with $T=7000^\circ$ and a small probable error. The measures of the $R$ branches are plotted in Fig. 4, from which it is clear that a vibrational temperature of 7000$^\circ$ requires intensities significantly in excess of the measured intensities for the 2-2, 3-3, and especially the 4-4 band. There are several possible explanations of this. First, there may be a considerable difference between the vibrational and rotational temperatures, but this should not be inferred from the above evidence alone. Secondly, if the assumed continuous background is too high then the intensities of the weaker lines and bands will have been reduced systematically, compared with the intensities of the stronger lines. Thirdly, if the continuous background has been correctly drawn then the vibrational–rotational temperature must be less than 7000$^\circ$. In this case, the measured intensities of the 0-0 band must either all be too great because of blending, which seems unlikely, or the intensities of the strongest lines, in addition to the band heads, must be depressed by self-absorption. The theoretical intensity distributions for 4000$^\circ$, drawn in Fig. 4, indicate that even such a low temperature as this might be possible if self-absorption is assumed to be sufficiently great.

It is clear from these results that the maximum possible excitation temperature for Level 1 is 7800$^\circ$, obtained on the assumption of the lowest possible continuous background. Raising the continuous background level necessitates a progressive lowering of the excitation temperature and an increase in effects which must be attributed to self-absorption. A reliable estimate of the continuous background level and quantitative knowledge of the effects of self-absorption are therefore required to fix the excitation temperature accurately.

5.4. Effective rotational temperatures of Levels 2 and 3.—The absence of a detectable continuous background on the intensity records of Levels 2 and 3 is a considerable advantage, but because of the weakness of the CN lines, errors in the photometry are proportionally greater. To minimise such errors, the zero intensity in the vicinity of each line was estimated from the original tracings. The line profile appropriate to Level 2 was then computed and the procedure followed for Level 1 employed to obtain the measured intensities in Fig. 5. The close agreement with a rotational temperature of 5000$^\circ$ is possibly fortuitous, as the band head exhibits a deficiency, probably due to self-absorption. However,
the intensity distribution for 7000° demonstrates that a temperature as high as this is most unlikely. The lines with $m > 75$ are too weak to be detected on the records, as are all the lines of the 3−3 and 4−4 $R$ branches. A few lines of the 1−1 and 2−2 bands are measurable, but not enough for a vibrational temperature to be obtained.

The CN lines at Level 3 are so weak that it was not feasible to construct line profiles, so the procedure used to obtain a preliminary temperature for Level 1 from the $0−0$ band had to be adopted. No attempt was made to detect lines in other bands. The measured intensities, converted to central ordinate intensity units, are plotted in Fig. 6 together with theoretical intensity distributions for 4000°, 5000° and 7000°. The measured intensities are maximum intensities, so a temperature of $4500° \pm 500°$ seems most likely and 7000° unreasonably high. As in the cases of Levels 1 and 2 there are indications that self-absorption affects the band head.

![Fig. 6.—CN $0−0$ band, Level 3: measured intensities (uncorrected line areas).](image)

6. Self-absorption.—Prima facie evidence for the presence of self-absorption in the flash spectrum is provided by the conspicuous reversal of intensity in the centres of many lines of quite moderate intensity, some of which can be seen in Plate 7. However, it must be emphasized that self-reversal can only occur where there is a negative excitation temperature gradient, whereas self-absorption is inseparable from line emission by a gas in local thermodynamical equilibrium (L.T.E.), although in an optically thin layer (by definition) its effects are negligible. The theoretical treatment of self-reversal is a difficult problem, but fortunately it is not directly observed in the CN lines, so it may be assumed initially that the chromospheric CN is in L.T.E. at a single temperature. Even so, a new approach to the problem of self-absorption is necessary because, while previous work has been concerned with the profiles or equivalent widths of single lines, the CN bands consist of doublets with varying separations and unresolved groups of lines.

In the absence of self-absorption, the "ideal" emitted intensity of each component of a particular CN doublet will be given by the relations quoted in Section 4. Each component will have a profile given by (5.1), and the total line profile will depend on the doublet separation. Self-absorption will modify the profile of the emitted line. The intensity records show the emitted self-absorbed line broadened by the known apparatus function, but unchanged in total intensity. In principle, therefore, the "ideal" intensity of each component of a CN doublet can be deduced from the intensity records if the relation between "ideal" and "self-absorbed" intensity is known. The "ideal" intensity of emission from
a cylinder of the chromosphere in L.T.E. at a temperature $T$ is

$$I' = B'_x(T) \tau_x$$  \hspace{1cm} (6.1)$$

where $B'_x(T)$ is the Planck function and $\tau_x$ is the optical thickness of the cylinder at the frequency $\nu$. Taking self-absorption into account, the intensity of emission from the same cylinder is

$$I_x = B_x(T) \{1 - \exp (-\tau_x)\}$$  \hspace{1cm} (6.2)$$

(see, e.g. Unsöld 1955). Hence the "self-absorbed" intensity is related to the "ideal" intensity by the equation

$$I_x = B_x(T) \{1 - \exp [-I'_x/B'_x(T)]\}$$  \hspace{1cm} (6.3)$$

Two difficulties prevent the straightforward application of these principles. First, the intensity records do not have an absolute intensity calibration, so $B_x(T)$ in (6.3) is not known in terms of the relative intensity units adopted. Secondly, the removal of the effect of the apparatus is a practical impossibility in the case of a band head, and even in the simpler case of an unresolved doublet it would require mechanical integration, as the instrumentally broadened self-absorbed profile is not a Voigt function. However, if a value for the temperature is assumed, a theoretical CN band can be computed completely using the appropriate intensity relations of Section 4 and either measured or calculated wavelengths. Assuming a value for the Planck function, the corresponding self-absorbed band can be completely computed using (6.3). The areas of the observed lines and line groups on the intensity records (with due allowance for blends) should be equal to the areas of the corresponding computed lines, provided the assumptions regarding temperature and Planck constant are correct and the scale of the computed band has been correctly chosen. Hence, by trial and error, it should be possible to determine (approximately) whether the CN emission is in accordance with a chromosphere in L.T.E. and, if it is, to find the value of the corresponding absolute intensity scale of the records and the effective excitation temperature. This procedure was applied to the CN o–o band at Levels 1, 2 and 3.

In order to compute a theoretical band it is necessary to know the frequencies of the lines in the unresolved portions of the band head. These have been calculated by Smit-Miessen and Spier (1942), and their values have been adopted for the whole of the $P$ branch. Doubtless separations were obtained as described in Section 5.3. A rotational temperature of 4500° was adopted, this being the temperature previously derived for Level 3, where self-absorption must be least, and also the temperature obtained by Hunaeerts (1947) from photospheric CN. The turbulence adopted was that appropriate to Level 1. The computed band need not be very accurate because the intensity records are subject to errors of many kinds already mentioned. It is therefore justifiable to take the positions of the lines correct only to the nearest millimetre (0.012 Å) on the records, considerably reducing the labour involved in the computations. Portions of the approximate band profile were computed in a comparatively short time. The portions selected were the band head as far as the 3878 Å Fe I line, a region which appears to be comparatively free from blends, the line $P$ (56) which is also well observed, and those $R$-branch lines having theoretical doublet separations of an integral number of millimetres. The computed band, on an arbitrary intensity scale, is shown in Fig. 7.
To construct a corresponding self-absorbed band, it is necessary to assume a value for the Planck function in the intensity units of Fig. 7*. From (6.3) it is obvious that if, at the band head, \( B_H \gg I_H' \), there will be hardly any self-absorption, while considerable self-absorption requires \( B_H < I_H' \), giving \( B_H \) not much greater than \( I_H' \). As a first estimate, \( B_H \) was taken to be 100 units.

![Fig. 7](image7.png)

**Fig. 7.**—Effect of self-absorption on the computed CN 0–0 band profile. \( (T=4500°; \tau_H=2.63) \).

![Fig. 8](image8.png)

**Fig. 8.**—Effect of self-absorption on the intensity distribution in the computed CN 0–0 band. \( (T=4500°; \tau_H=2.63) \).

* Because the intensity gradient in the chromosphere depends on the emitting element, the effective height and absolute intensity scale of the Level 1 spectrum are not the same for all elements. Hence, when considering the CN emission, it is incorrect to assume that the Planck function is approximately equal to the peak intensities of strongly self-absorbed lines such as H\( \beta \).
on the intensity scale of Fig. 7; this is equivalent to assuming the optical depth at the band head to be $\tau_H = 2.63$. The corresponding self-absorbed band in Fig. 7 was then computed.

The intensities of corresponding lines in the "ideal" and self-absorbed bands were obtained from their areas, and the intensity distributions plotted in Fig. 8. A quick glance at Figs. 2, 3 and 5 shows that the computed self-absorption produces an effect at least of the right order. While the self-absorption at the band head amounts to nearly 50 per cent, the intensity distribution in the self-absorbed $R$ branch corresponds very closely to a rotational temperature of 4800°. This indicates that whatever the true temperature, unless self-absorption at the band head is very much greater than 50 per cent (i.e. $\tau_H \gg 2.6$), the rotational temperature obtained from the $R$ branch neglecting self-absorption will not be very much too high. On this account, agreement of the measured intensity distribution at Level 1 with the self-absorbed band computed for an assumed temperature of 4500° would not be expected—indeed, it was found to be quite impossible to reconcile the two, whatever value of $\tau_H$ was adopted. Unless the assumption of L.T.E. is seriously incorrect, either the emission from Level 1 is due to an atmosphere at a uniform higher temperature or there is a negative excitation temperature gradient. The lower temperatures already obtained for the higher levels show that the latter alternative is probably correct. Thus it was not considered worth while undertaking a further computation of the band for a higher temperature.

![Figure 6](https://example.com/figure6.png)

**Fig. 6.**—CN 0–0 band, Levels 2 and 3: comparison of computed self-absorbed intensity distributions ($T=4500°$) with measured intensities.

Several different values of $\tau_H$ were also tried to obtain the best possible agreement between the computed self-absorbed intensity distribution and the measured distribution at Levels 2 and 3. The best fits, obtained with $\tau_H = 3.5$ and 1.8 respectively, are shown in Fig. 9. The good agreement in the case of Level 3, when allowance is made for possible blends, shows that the CN 0–0 band on the intensity records is consistent with L.T.E. and a temperature of 4500°. The actual value of $\tau_H$ is not critical; for a range of $\tau_H$ from 1.5 to 2.5 there is
little variation in the resulting agreement, so small errors in the computed band profile will have little effect upon the result. Such errors will arise from the inaccuracy of the adopted line positions and the use of the Level 1 profile (the true Level 3 profile is wider because of the increase of turbulence with height detected by Redman and Suemoto).

For Level 2 the agreement is satisfactory except in the immediate vicinity of the band head. Again the value of $\tau_H$ between 3 and 4 is not critical, so the discrepancy at the band head cannot be ascribed to experimental errors. The CN emission from Level 2 may therefore correspond to a uniform temperature somewhat higher than $4500^\circ$, or there may be a negative excitation temperature gradient. The latter possibility seems the more likely, in view of the temperature of $4500^\circ$ now established for Level 3.

7. Discussion and conclusions.—Correlating the results for the three levels studied it appears that, assuming L.T.E. and taking self-absorption fully into account, a definite excitation temperature can be ascribed only to Level 3. The CN spectrum is in agreement with an excitation temperature $\approx 4500^\circ$ at an effective height $\approx 400$ km. The results obtained from Levels 1 and 2 can be interpreted as indicating a negative excitation temperature gradient, the temperature being greater than about $4500^\circ$ at an effective height $\approx 50$ km, and less than about $7000^\circ$ at an effective height $\approx 0$ km. The value of the temperature gradient cannot be determined without detailed consideration of the emission and absorption by an optically thick chromosphere with a negative temperature and density gradient—a problem which has not yet been attempted.

The excitation temperatures obtained above may be compared with those obtained by the authors mentioned in Section 1. The agreement with Parker’s rotational temperature of $4600^\circ \pm 400^\circ$ for an estimated effective height $< 500$ km, is very satisfactory. Blackwell’s temperatures of between $5000^\circ$ and $7500^\circ$ refer to an effective height of $1500$ km and cannot be directly compared with the present results.

Superficially, Pecker and Athay’s rotational temperature $\approx 4500^\circ$ at an effective height of $100$ km appears to be in good agreement with the present results, but detailed examination of their paper reveals otherwise. Pecker and Athay’s results are based on an analysis of the region between the $0-0$ band head and the $3878$ A Fe I line on slitless spectrograms. The resolution and dispersion are greatly inferior to those of Redman’s spectrogram, and the region consequently presents an irregular and unresolved profile. The “rotational temperature” was determined from the peak intensities of the irregularities in the profile, the peaks being identified with the lines of the proceeding portion of the $P$ branch. This procedure cannot be justified. In the absence of self-absorption, the observed band profile depends on the following factors: (1) the relative intensities (defining the effective rotational temperature) of the lines of both the proceeding and returning portions of the $P$ branch, the latter being just as important as the former; (2) the separation of the lines, which decreases towards the band head; (3) the separation of the individual components of the doublet, which increases with increasing $|m|$; (4) the emitted line profile; (5) the instrumental profile.

With a wide instrumental profile, such as that effective in producing Pecker and Athay’s spectra, the combination of these five factors results in a band profile with peaks which cannot be identified, either in position or intensity, with the low $m$-number lines. This is clearly demonstrated by Fig. 10, which is identical
with the computed "ideal" band in Fig. 7, except that the line profile is rectangular and equal in width to that assumed by Pecker and Athay. If their assumptions and results are correct, the band profile in Fig. 10 must be almost identical with that of their eclipse spectrograms.

![Diagram](https://example.com/diagram.png)

**Fig. 10.**—Computed CN 0-0 band profile \((T=4500^\circ)\), smoothed by a wide instrumental profile.

An attempt was made to determine the rotational temperature from Fig. 10, following exactly the procedure adopted by Pecker and Athay: the result was a negative temperature. The correct conclusion to be drawn from their data is that the region of the 0-0 band head exhibits an intensity distribution which is very far from being in accord with a rotational temperature of 4500°, when self-absorption is neglected. It would appear that self-absorption affects the band profile to just such an extent that Pecker and Athay's wrong analysis, quite fortuitously, gives approximately the right answer.

The above discussion does not, of itself, invalidate Pecker and Athay's detection of a positive temperature gradient from their spectrograms. However, this was deduced from an increase in the observed general slope of the band profile, an effect which will be produced by the certain decrease of self-absorption with height. Their measures do not necessarily indicate a positive temperature gradient*.

If strict L.T.E. holds throughout the regions considered, as assumed in the discussion of self-absorption, then the approximate excitation temperatures for the CN emission must be equated to the kinetic temperature at each height. There must therefore be a negative kinetic temperature gradient in the chromosphere, the temperature being defined as \(\approx 4500^\circ\) at a height \(\approx 400\) km, with the value of the gradient uncertain. However, de Jager's (1957) most recent and reliable chromospheric model requires a positive kinetic temperature gradient, although the temperature of 4650° at 400 km agrees very well with the above results. Pagel (1956) has also obtained a positive temperature gradient, his temperatures being somewhat higher than de Jager's, due to the neglect of

* Pecker, in a private communication, has subsequently expressed a general agreement with these criticisms, but he has suggested that the observed band profile could be caused by the mixing of radiation from optically thin layers at different temperatures. However, although temperature inhomogeneities may well be present they could not alone explain the band profiles in Redman's spectrogram.
turbulence. It is clear that an analysis of the CN emission based upon L.T.E. and the general run of de Jager's kinetic temperatures will lead to a negative excitation temperature gradient contradicting the original assumptions. Thus, the hypothesis of L.T.E. is not self-consistent and must be abandoned.

The opposite extreme to purely thermal emission would be a chromospheric spectrum which is simply the scattered photospheric spectrum. At first sight, the $\theta$--$\theta$ band head at zero height would appear to support such a hypothesis, as it is almost exactly the mirror image of the band head in the Utrecht Atlas (Minnaert, Mulders and Houtgast 1940). However, Hunaerts' (1947) rotational temperature for the $\theta$--$\theta$ R branch in the Utrecht Atlas is $4464^\circ \pm 117^\circ$, which does not agree with the $\approx 7000^\circ$ deduced originally for zero height. In any case, if all the photospheric light were scattered by the bottom layers of the chromosphere, there would be none left to account for the spectrum at greater heights.

An intermediate possibility, first suggested privately by Pagel, is that most of the CN absorption might occur in the chromosphere. The bottom layers would then be excited by dilute radiation from the photosphere with a colour temperature of 6700$^\circ$ (Canavaggio and Chalonge 1946), which would determine the distribution of molecules amongst the various rotational and vibrational levels of the upper electronic state. With the formation of absorption lines in the lowest layers, the exciting radiation would be quickly depleted at the vital frequencies, so that ultimately the absorption spectrum of the centre of the disk would be controlled by the kinetic temperature (assumed to be $\approx 4500^\circ$ at heights above 100 km). The excitation temperature of the emission from these heights would be the same as the kinetic temperature, i.e. $\approx 4500^\circ$. The intensity distribution of the emission from zero height would correspond to an excitation temperature of 6700$^\circ$, but would be modified by absorption by the cooler overlying layers. Also, if appreciable absorption at the band heads already existed in the high photosphere, the rotational levels $20 \leq K^' \leq 35$ would be under-populated and the emission from these levels would be depleted. The final result would be an apparent excitation temperature $\approx 7000^\circ$ with depressed band heads, as observed.

An insurmountable difficulty, which prevents the adoption of the above explanation, is that the tangential optical depths in the chromosphere, being of the order 1 for strong lines, are altogether too small to account for the radial optical depths in the photospheric spectrum, which must also be of the order 1. The bulk of the CN absorption therefore takes place in the photosphere. A complete evaluation of the CN emission and absorption should start in the low photosphere, before any CN molecules have been formed, and progress upwards with the kinetic temperature, density, pressure, and partial pressure of CN all varying; excitation both by radiation and collisions must be considered. Such an analysis cannot be attempted at present.

The interpretations attempted or suggested above all assume implicitly that the recorded CN emission can be attributed to a certain effective height or range of heights in the chromosphere. It has already been pointed out (Section 6) that the effective height of any level depends on the intensity gradient of the line considered. The variation of self-absorption with "ideal" line intensity and with chromospheric height produces a steeper intensity gradient for weak lines than for strong lines of the same element. Hence, the CN band heads must refer to a greater effective height than the weak lines, and the absolute intensity scales for each must also be different. A comparison of the intensities of CN lines therefore
has little meaning, except as a rough approximation. It would be difficult to assess the magnitude of the effects of these considerations upon the present work. However, it is clear that the result must be a depression of the intensities of the band heads and the strong lines relative to those of the weak lines at the same level. Thus the chromospheric CN emission may not be inconsistent with de Jager's kinetic temperatures if departures from L.T.E. and the imperfection of the observational data are taken into account.

If the experimental and analytical difficulties could be overcome, the CN bands would yield a wealth of information about the transition region between the photosphere and the chromosphere. Ideally, one would like to have spectrograms of the mottles, and the regions between them, from the centre of the disk to the limb—also high-resolution flash spectra with absolute intensity calibrations, taken in the best possible observing conditions (from balloons or rockets, perhaps). It is unlikely that such data will be available in the near future. In the meantime, it is doubtful if much further progress can be made with the interpretation of solar CN spectra.

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